Report No. SR88-12-01b

A Study of Excess Motor Vehicle Emissions - Causes and Control

Volume I (Sections I-V)

Heavy-Duty Diesel NOx and Particulate Control Technologies

Enforcement Alternatives for Heavy-Duty Engine Emission Standards

The Feasibility of a Heavy-Duty Gasoline Truck Inspection and Maintenance Program

Evaluation of "Expert Systems" and Test Analyzer System Enhancements for the California Smog Check Program

Evaluation of Factors Affecting Catalyst Durability in Light-Duty Vehicles

ARB Contract No. A5-188-32

prepared for:

State of California Air Resources Board

December 1988

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PREFACE

This report presents the results of a major research study addressing the causes of excess emissions from California vehicles. The effort produced ten separate reports. This volume contains the first five reports produced under the contract. They are:

Title	Section
Heavy-Duty Diesel NOx and Particulate Control Technologies	I
Enforcement Alternatives for Heavy-Duty Engine Emission Standards	II
The Feasibility of a Heavy-Duty Gasoline Truck Inspection and Maintenance Program	III
Evaluation of "Expert Systems" and Test Analyzer System Enhancements for the California Smog Check Program	IV
Evaluation of Factors Affecting Catalyst Durability In Light-Duty Vehicles	V

The remainder of the reports produced under this contract are contained in Volume II. For an overview of all of the work produced under the contract, the reader is referred to:

> Executive Summary of Work Produced Under ARB Contract "A Study of Excess Emissions - Causes and Control", December 1988.

A STUDY OF EXCESS MOTOR VEHICLE EMISSIONS -
CAUSES AND CONTROL

VOLUME I

Table of Contents

Section

Volume I
Table of Contents, continued

RADIAN
CORPORATION

245-050-01

SECTION I

A STUDY OF EXCESS MOTOR VEHICLE EMISSIONS

HEAVY DUTY DIESEL NO_x AND PARTICULATE CONTROL TECHNOLOGIES

FINAL REPORT

ARB Contract No. A5-188-32

Submitted to:

California Air Resources Board
1800 15th Street
P.O. Box 2815
Sacramento, CA 95812

Prepared by:

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RADIAN
CORPORATION

TABLE OF CONTENTS

LIST OF TABLES

RADIAN
CORPORATION

LIST OF FIGURES

1.0 INTRODUCTION

Highway vehicles account for a large fraction of the air pollutant emissions inventory, in California as in most other states. As increasingly stringent controls are applied to passenger cars and light trucks, the contribution of the relatively uncontrolled heavy-duty vehicles has become more conspicuous. Virtually all buses and all of the heaviest class of trucks are diesel powered, as are an increasing fraction of the lighter classes of heavy-duty trucks.

Heavy-duty diesel engines emit very little carbon monoxide (CO) for their size and only moderate amounts of unburned hydrocarbons (HC). Diesel oxides-of-nitrogen (NO_x) emissions are as great or greater than those from comparable gasoline engines, however. Diesels also emit significant amounts of particulate matter (PM), virtually all of which falls within EPA's and ARB's definition of inhalable or fine particulate. Visible smoke and odor from diesel engined vehicles are also common causes of public offense, and major sources of complaints to air pollution control agencies.

In order to limit these emissions and reduce their effects on ambient air quality, both the California Air Resources Board (ARB) and the Federal Environmental Protection Agency (EPA) have adopted regulations limiting pollutant emissions from new heavy-duty diesel engines. The most recent regulations--adopted in 1985 and 1986, and taking effect in 1988, 1991, and 1994--have forced the rapid development of emissions controls for heavy-duty diesel engines. This report documents the results of a Radian Corporation study of the current status of diesel emissions control technology, performed under subcontract for the California ARB.

1.1 <u>Emissions Regulations For Heavy-Duty Diesel Engines</u>

Table 1-1 shows the California and Federal emissions limits established for heavy-duty engines of various model years. Due to the variety of

TABLE 1-1. FEDERAL AND CALIFORNIA EMISSIONS REGULATIONS FOR HEAVY-DUTY DIESEL ENGINES

	CO (g/BHP-hr)	HC (g/BHP-hr)	NO_x (g/BHP-hr)	PM (g/BHP-hr)	Test Procedure	Smoke Opacity (Acc/Lug/Peak, %)
<u>Federal</u>						
1974-1978	40		16[a]	NR	13-Mode	20/15/50
1979-1984	25	1.5	10[a]	NR	13-Mode	20/15/50
1985-1987	15.5	1.3	10.7	NR	Transient	20/15/50
1988-1989	15.5	1.3	10.7	0.6	Transient	20/15/50
1990	15.5	1.3	6.0	0.6	Transient	20/15/50
1991-1993	15.5	1.3	5.0	0.25	Transient	20/15/50
1994+	15.5	1.3	5.0	0.1	Transient	20/15/50
<u>California</u>						
1973-1974	40		16[a]	NR	13-Mode	b
1975-1976	30		10[a]	NR	13-Mode	b
1977-1979	25	1.0	7.5	NR	13-Mode	b
1980-1983	25	1.0	6.0[a]	NR	13-Mode	b
1984-1987	15.5	1.3	5.1	NR	Transient	b
1988-1990	15.5	1.3	6.0	0.6	Transient	b
1991-1993	15.5	1.3	5.0	0.25	Transient	b
1994+	15.5	1.3	5.0	0.1	Transient	b

NR: Not regulated

[a] Sum of NO_x plus HC emissions.

[b] Federal Smoke Standard

heavy-duty truck models, equipment options, and duty cycles, it would be impractical to specify heavy-duty emissions limits in terms of pollution per unit of distance travelled (e.g. grams/mile), as is done with light-duty vehicles. For this reason, heavy-duty emissions regulations are written to apply to the engine, rather than to the vehicle, and are expressed in terms of units of pollution per unit of work done by the engine, as measured over a specified test cycle on an engine dynamometer. Currently, only gaseous emissions and diesel smoke opacity are regulated, but new Federal and California limits on diesel particulate emissions are scheduled for model year 1988.

Test procedures--The test cycles and other procedures under which emissions are measured are as important as the numerical emissions limits shown in Table 1-1. Until recently, gaseous emissions were measured on the "13-mode" cycle, which involved operating the engine in steady state at nine different power and speed settings, with intervening periods of idle operation. This was superseded for diesel engines by the current Federal Heavy-Duty Transient Test cycle, in which engine speed and load are continually varied according to a fixed schedule in order to simulate a typical urban driving pattern. Since diesel HC and particulate emissions can increase dramatically during engine transients and cold starts, the Heavy-Duty Transient test procedure is considered to give measurements more representative of in-use operation than the old 13-mode cycle.

Diesel smoke opacity is measured in a separate test procedure. This procedure simulates an acceleration from stop, followed by a gear change and continued acceleration, followed by "lugging down" from full engine power to the maximum torque point. This procedure measures only the occurrence of offensively high visible smoke levels--the correlation between the smoke measurements and average particulate mass emissions in new engines is poor. Meeting the new Federal and California particulate standards will require major reductions in visible smoke, and should result in much lower smoke levels than those specified in the Federal smoke standards.

Impact of regulations--Of the current gaseous emission limits shown in Table 1-1, only the California NO_x limit has much relevance for diesels. As the "typical" emissions values show, diesel engines can easily comply with the HC and CO limits set, and most Federal engines are certifying NO_x levels well below the applicable standard of 10.7 g/BHP-hr.

Diesel engine designers have faced a significant challenge in complying with California's 1988 NO_x and particulate standards, however. While existing engines at the time these standards were adopted could readily comply with either the 6.0 g/BHP-hr NO_x standard or the 0.6 g/BHP-hr particulate standard, the tradeoff relationship between NO_x and particulate emissions required technological advances in order to meet both standards together. Meeting the 1991 and 1994 emissions standards will require further major advances in emissions control technology. The prospects for meeting these standards and the technologies required to do so are the major topics of this report.

Useful life--For 1988 and subsequent years, EPA and ARB regulations require that engines must comply with the applicable emission limits over their EPA-defined "full useful lives." Three classes of heavy-duty engines have been defined for the purpose of useful life determination: light-heavy duty, with a specified useful life of 110,000 miles; medium-heavy duty, 185,000 miles; and heavy-heavy duty, 290,000 miles. These engine classifications correspond closely to the vehicle classifications discussed above--light-heavy engines are typically used in light-heavy vehicles, medium-heavy engines in medium-heavy vehicles, and so forth. Provisions for in-use audits to ensure compliance with the useful-life requirements, and possible penalties and/or recall if the requirements are found not to be met, are also included in the regulations.

The EPA-defined "useful life" for medium-heavy and heavy-heavy duty engines is reasonably representative of the mileage to the first overhaul. There is presently no effective regulation of heavy-duty engine emissions after overhaul. Since all of the critical emissions-related components on a heavy-duty engine are rebuilt or replaced during overhaul, this omission may be significant. Engine rebuilding practices that may affect emissions have been investigated by another ARB contractor (Sierra Research, 1987).

1.2 Purpose and Scope of This Report

This report fulfills the requirements of Task 1, Subtasks A and B of a joint Radian/Sierra Research project to evaluate the causes and control of excess motor vehicle emissions in California. This work was performed for the California Air Resources Board under contract No. A5-188-32.

The specific objectives of this work were the following:

1. Update an earlier study of heavy-duty diesel emissions control technology prepared by one of the authors (Weaver et al., 1984) to reflect recent technical developments and trends;

2. Evaluate industry progress toward compliance with the 1991 and 1994 emissions standards, and assess related regulatory issues; and

3. Assess the feasibility of meeting heavy-duty diesel emissions standards lower than the current 1994 levels of 0.1 g/BHP-hr particulate matter and 5.0 g/BHP-hr NO_x, and estimate the costs, cost-effectiveness and lead-time requirements for compliance.

This report is based on a thorough review of the applicable technical literature and in-person discussions and confidential written materials submitted by all major domestic and a number of foreign manufacturers of heavy-duty diesel engines.

1.3 Guide to the Remainder of the Report

This report is divided into eight sections, of which this Introduction is the first. Section Two, following, provides background material on heavy-duty vehicles and engines, to set the stage for the more technical discussions which follow. Section Three provides an overview of the current state of the art in diesel emissions control. Specific elements of emissions control technology are examined in detail in Sections Four (in-cylinder control technologies), Five (trap-oxidizers), and Six (other aftertreatment technologies). These sections update the discussion in Weaver et al. (1984), to reflect recent progress.

Section Seven discusses several significant regulatory issues which became apparent during the course of the study. These include diesel fuel sulfur content, concerns with by-passable trap-oxidizers, and the question of whether the current particulate mass standards are the best way of achieving ARB's regulatory goals. Potential new NO_x and particulate emissions standards for heavy-duty diesel engines, and the technology required to achieve them, are discussed in Section Eight.

1.4 Limitations and Caveats

The conclusions and analysis in this report are based on a thorough review of the applicable technical literature, and on numerous confidential discussions and submissions by engine manufacturers. Much of the analysis is based on manufacturer's proprietary data. For confidentiality reasons, this information can be discussed only in vague and general terms.

The research and development results supplied by the individual manufacturers are the most up-to-date information available on diesel emissions control, but they may not necessarily be complete. Manufacturers could conceivably have withheld information on promising developments (especially if their outcome is uncertain) either for competitive reasons or in hope of influencing regulations. While this possibility cannot be completely ruled out, we consider it unlikely that any significant technologies have been thus concealed. The large number of manufacturers supplying data and the technical depth and apparent candor of the manufacturer's discussions would have made it very difficult to conceal any significant developments.

This report attempts to assess the current "state of the art" of diesel emissions control. The reader is cautioned that not all engine manufacturers are working at the "state of the art"--there are leaders and laggards, as in any field. Further, no one manufacturer is employing or has even tested all of the advanced technologies described here, nor would the implementation of all of these technologies in a single engine be practical. Our evaluation of the prospects, problems, and opportunities for emission controls has thus necessarily involved considerable engineering judgement. Such judgements are subject to error. For example, similar judgements in the earlier 1984 report by Weaver and co-workers proved considerably over-conservative in estimating the extent of in-cylinder emissions control feasible.

This report considers only heavy-duty diesel-cycle engines fueled with petroleum middle-distillate ("diesel") fuel. Lower emission standards may be feasible through the use of methanol or other alternative fuels in engines designed for them. At sufficiently low NO_x standards, these engines may become cost-competitive with diesel engines on a life-cycle basis. Alternative-fuel engines and their potential are beyond the scope of this report, however.

This report considers only engine emission levels as determined by the EPA and/or ARB emissions certification process. Experience has shown that in-use emissions from all types of engines, including heavy-duty diesels, are significantly greater than certification emissions. This results from the effects of production tolerances in manufacturing; user tampering with emission controls; poor, mal-, or non-maintenance; use of poor quality fuel; and other causes. The effects of tampering and malmaintenance on in-use emissions are discussed in another Radian report to the ARB (Weaver and Klausmeier, 1987a). Some of the implications of in-use deterioration for the cost-effectiveness of the 1994 particulate standard are addressed in Section Seven.

2.0 BACKGROUND INFORMATION: HEAVY-DUTY DIESEL VEHICLES AND ENGINES

This Section provides an overview of heavy-duty diesel vehicle classification, diesel engine technology, and the fundamentals of diesel pollutant formation and destruction in the engine. It is intended to supply background information for those previously unfamiliar with the area, and to establish definitions for the more technical chapters which follow.

2.1 Heavy-Duty Vehicle Characteristics

For regulatory purposes, highway vehicles are divided into two major classes: light-duty vehicles and heavy-duty vehicles. Light-duty vehicles include passenger cars and all trucks having a manufacturer's rated gross vehicle weight (GVW) less than 8,500 pounds. Trucks and buses with a rated GVW of 8,500 pounds or more are classed as heavy-duty vehicles. Light-duty vehicles have been subject to increasingly stringent emission-control regulation over the past two decades. Heavy-duty vehicles have only recently begun to experience a similar level of regulatory interest.

Vehicles classed as "heavy-duty" span an enormous range of sizes and uses. They range from pickups and vans which are basically uprated versions of light-duty vehicles to huge tractors towing multiple trailers rated at 150,000 pounds gross combined weight. One commonly used system for classifying these vehicles was developed by the Motor Vehicle Manufacturer's Association (MVMA). Classification is on the basis of GVW, and ranges from Class 1 (0-6000 lb GVW) to Class 8 (33,001 lb GVW and up). In emissions work, MVMA Class 2 (6001-10,000 lb GVW) is commonly subdivided into Classes 2a (6001-8,500 lb) and 2b (8,501-10,000 lb) to separate vehicles classed as light and heavy-duty by EPA. This classification system is diagrammed in Figure 2-1.

Although it is simple and widely used, the MVMA classification system does not adequately reflect current heavy-duty vehicle classes. Almost no vehicles are produced in MVMA classes 3 and 4, for instance, while class 8

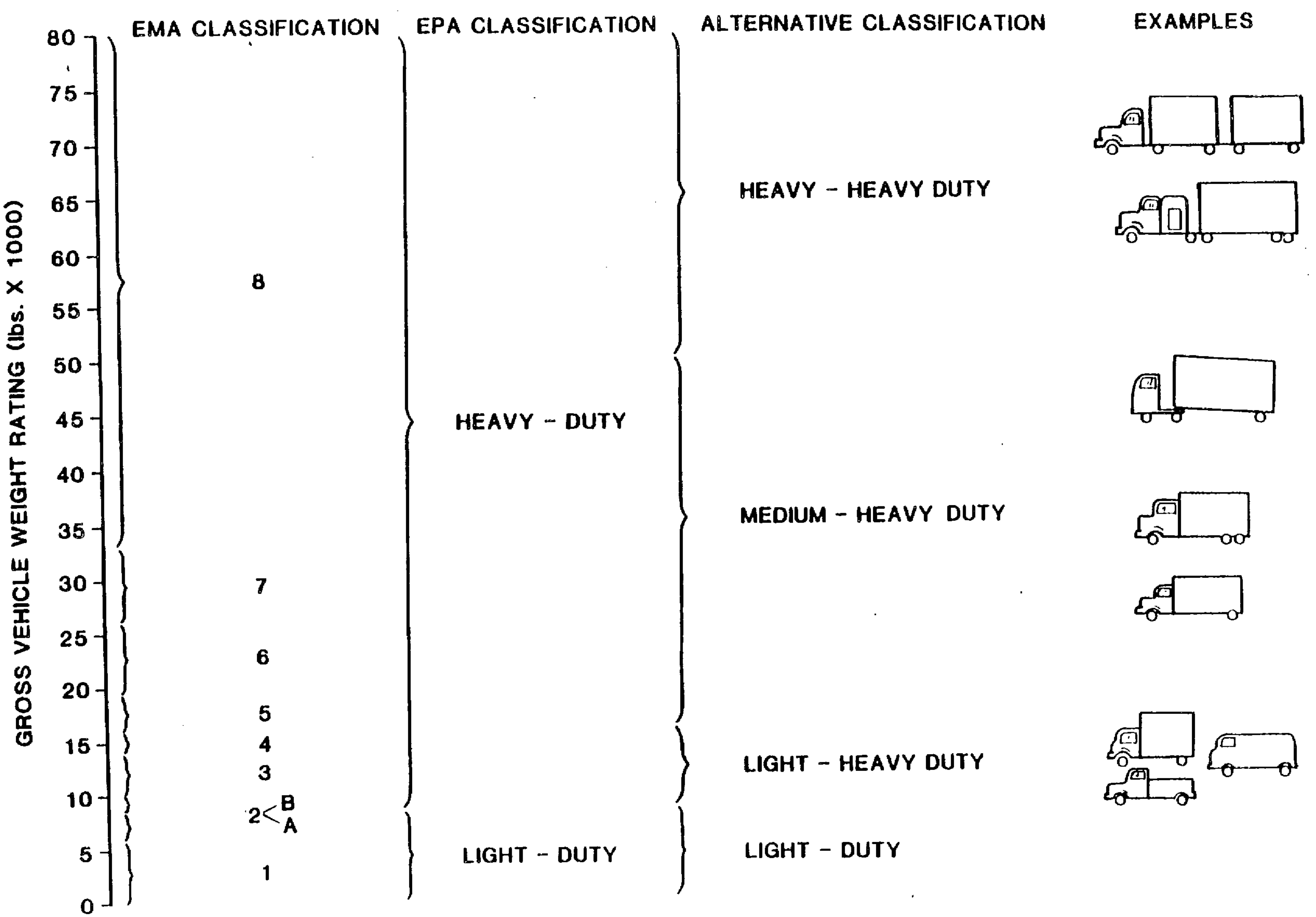


Figure 2-1. Heavy-Duty Vehicle Classification

lumps together many different kinds of heavy trucks, some of which have very different design and usage characteristics. Because of these problems, an alternative classification system--also shown in Figure 2-1--has come into increasing use. In this system, heavy-duty trucks are divided along both size and functional lines into three classes: light-heavy, medium-heavy, and heavy-heavy. Because of their unique ownership and operating characteristics, transit buses are treated separately, as a fourth class.

Light-heavy duty vehicles are mostly large pickups and vans, and specialty vehicles (such as motor homes) built on pickup and van chassis. The engines, production methods, and usage patterns in this class closely resemble those in light-duty vehicles. Most vehicles in this class are still gasoline powered. Diesel engines are commanding an increasing share of the market, however, making this the most rapidly growing class of diesel vehicles.

Medium-heavy duty vehicles include school buses, nearly all single-unit trucks, and light (so-called "city") truck-tractors. These are trucks intended mostly for pick-up and delivery, stop-and-go operation in cities under moderate load. Heavy-heavy duty vehicles, on the other hand, are large, heavy, and very powerful trucks intended primarily for long-distance freight and heavy hauling applications. Virtually all are heavy tractor/trailer or truck/trailer combinations.

Transit buses fall into the same weight and size classification as medium-heavy duty vehicles, but their unique operating patterns and areas of operation result in a disproportionate impact on urban air quality. It has been estimated (Chock et al.,1984) that buses may account for as much as 40 percent of all diesel particulate matter measured in congested urban areas. Buses have accordingly been singled out for special attention, both by emissions analysts and by EPA regulations.

Industry structure--The U.S. medium-heavy and heavy-heavy truck industry is unique. Unlike the producers of light-duty and light-heavy duty vehicles, the manufacturers of U.S. medium-heavy and heavy-heavy duty trucks are largely custom assemblers of major subassemblies produced by others. A truck purchaser can typically choose among several engine models from two or three different manufacturers. One of these manufacturers may or may not be the same corporation as the truck builder. GMC trucks, for instance, are commonly offered with Cummins and Caterpillar as well as Detroit Diesel engines. Cummins and Caterpillar--the two largest heavy-heavy duty engine builders--produce no trucks; many of the largest heavy-heavy truck builders produce no engines. A similar degree of disaggregation exists for truck transmissions, drive axles, and specialized truck bodies.

2.2 Diesel Engine Technology

Diesel engines used in light-heavy duty vehicles mostly resemble those used in light-duty trucks. Medium-heavy and heavy-heavy duty engines and vehicles (including transit buses) are distinctly different from light-duty engines in technology, durability, and usage patterns. Premium features such as such as turbocharging, aftercooling, and four-valve cylinder heads--all new in the light-duty market--have been common for some time in heavy-heavy duty engines.

These engines are also built to higher standards of efficiency and durability than light-duty or light-heavy duty engines. Thermal efficiencies exceeding 40 percent (comparable to the best fossil-fuel power plants) are common in heavy-heavy engines, and engines in normal service may operate from 200,000 to more than 400,000 miles before they are worn out. The costs of these engines reflect these qualities--a medium-heavy duty engine costs $5,000 to $10,000 or more, and a premium heavy-heavy engine may cost more than $20,000.

In addition to being extremely durable to begin with, many medium-heavy and all heavy-heavy engines are designed to be overhauled and rebuilt easily. Removable cylinder liners are standard on heavy-heavy engines, for instance. With proper care, these engines can be rebuilt and reused indefinitely, and it is not at all unusual for a heavy-heavy truck engine to accumulate three rebuilds and more than a million miles during its lifetime. This has profound implications for in-use emissions, since (depending on the practices followed) rebuilding the engine may significantly change its emissions characteristics.

Combustion Systems--Diesel engines used in heavy-duty vehicles use several different types of combustion systems. The most fundamental difference is between direct injection (DI) engines and indirect injection (IDI) engines. Figure 2-2 shows a typical combustion chamber of each type. DI engines can also be divided into high-swirl and low-swirl (quiescent chamber) designs.

In an indirect-injection engine, fuel is injected into a separate "prechamber," where it mixes and partly burns before jetting into the main combustion chamber above the piston. In the more common direct-injection engine, fuel is injected directly into a combustion chamber hollowed out of the top of the piston. Fuel-air mixing in the direct-injection engine is limited by the fuel injection pressure and any motion imparted to the air in the chamber as it entered.

In high-swirl DI engines, a strong swirling motion is imparted to the air entering the combustion chamber by the design of the intake port. These engines typically use moderate-to-high injection pressures, and three to five spray holes per nozzle. Low swirl engines rely primarily on the fuel injection process to supply the mixing. They typically have very high fuel injection pressures and six to nine spray holes per nozzle.

In the indirect-injection engine, much of the fuel-air mixing is due to the air swirl induced in the prechamber as air is forced into it during compression, and to the turbulence induced by the expansion out of the prechamber during combustion. These engines typically have better high-speed

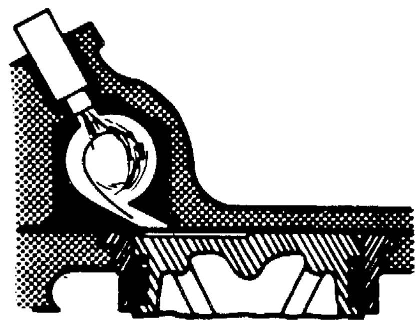


Figure 2-2a. Indirect injection.

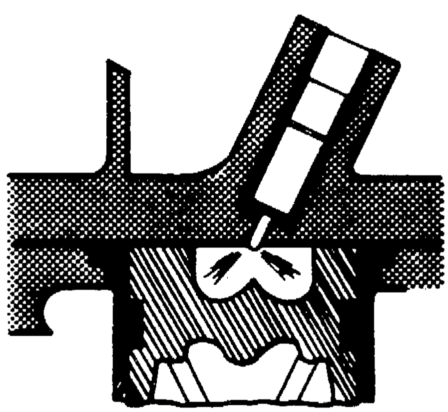


Figure 2-2b. Direct injection.

Figure 2-2. Diesel Engine Combustion Systems.

performance than direct-injected engines, and can use cheaper fuel-injection systems. Historically, IDI diesel engines have also exhibited lower emission levels than DI engines. With recent developments in DI engine emission controls, however, this is no longer the case. Disadvantages of the IDI engine are the extra heat and frictional losses due to the prechamber. These result in a 5-10 percent reduction in fuel efficiency compared to a DI engine.

Presently, all light-duty and most light-heavy duty diesels in the U.S. use IDI engines, but all medium-heavy and heavy-heavy engines are direct-injected. Most European and Japanese truck engines, and most medium-heavy U.S. truck engines are of the high swirl type, while most heavy-heavy U.S. engines are low-swirl designs. A number of advanced, low-emitting and fuel-efficient high-swirl DI engines have recently been introduced in the light-heavy duty category as well, so the share of this category held by IDI engines is likely to decline. Small, low-emitting, high-speed DI engines (of the high-swirl design) have also been developed for light-duty trucks and passenger cars (Wade et al., 1985).

<u>Fuel Injection Systems</u>--The fuel injection system in a diesel engine includes the machinery by which the fuel is transferred from the fuel tank to the engine, then injected into the cylinders at the right time for optimal combustion, and in the correct amount to provide the desired power output. The quality and timing of fuel injection dramatically affect the engine's power, fuel economy, and emissions characteristics, so that the fuel injection system is one of the most important components of the engine.

The fuel injection system normally consists of a low pressure pump to transfer fuel from the tank to the system, one or more high-pressure fuel pumps to create the pressure pulses that actually send the fuel into the cylinder, the injection nozzles through which fuel is injected into the cylinder, and a governor and fuel metering system. These determine how much fuel is to be injected on each stroke, and thus the power output of the engine.

Three generic types of fuel injection systems are in common use. These are:

1. Systems with distributor-type fuel pumps, in which a single pumping element is mechanically switched to connect to high-pressure fuel lines leading to each cylinder in turn;

2. Systems with unitary fuel pumps having one pumping element per cylinder, connected to the injection nozzle by high-pressure fuel lines (often called "in-line pumps"); and

3. Systems using unit injectors, in which the individual pumping element for each cylinder is combined in the same unit with the injection nozzle, eliminating the high-pressure lines.

Distributor pumps are relatively inexpensive, but they are limited in the injection pressures they can achieve. For this reason, they are used mostly in indirect-injection engines. In-line pumps are capable of much higher injection pressures. Mack, Navistar, Caterpillar, Ford and nearly all European and Japanese diesel manufacturers use in-line pumps. Unit injector systems are capable of the highest injection pressures (exceeding 25,000 PSI). They are used in Cummins and Detroit Diesel-Allison (DDA) truck engines, and in many large off-highway diesels.

Distributor and in-line injection pumps are typically driven by a special driveshaft from the engine timing gears. This allows the injection timing to be varied by rotating the pump with respect to its driveshaft, using a sliding helical spline. The pumping elements in unit injector systems are driven by the engine camshaft, in the same way as the intake and exhaust valves. Until recently, injection timing in unit injector systems has been fixed by the system geometry (except for the effects of wear). However, both Cummins and DDA have recently introduced variable injection timing systems for their engines. These are discussed in Section 4.1.

2.3 Diesel Emissions Fundamentals

Diesel engines emit significant quantities of oxides of nitrogen (NO_x), sulfur oxides (SO_x), and particulate matter; and lesser--but still significant--quantities of unburned hydrocarbons (HC). The NO_x, HC, and most of the particulate emissions from diesels are formed during the combustion process, and can be controlled by appropriate modifications to that process. The sulfur oxides, in contrast, are derived directly from sulfur in the fuel, and the only feasible control technology is to reduce fuel sulfur content. Most SO_x is emitted as gaseous SO_2, but a small fraction (typically 2-3 percent) occurs as particulate sulfates.

Diesel particulate matter consists mostly of three components: soot formed during combustion, heavy hydrocarbons condensed or adsorbed on the soot, and particulate sulfates. In older diesels, soot was typically 40 to 80 percent of the total particulate mass, but developments in in-cylinder emissions control have reduced the soot contribution to particulate emissions considerably. Most of the remaining particulate mass consists of heavy hydrocarbons adsorbed or condensed on the soot. This is referred to as the soluble organic fraction of the particulate matter, or SOF. The SOF is derived partly from the lubricating oil, partly from unburned fuel, and partly from compounds formed during combustion. The relative importance of each of these sources is controversial, and varies from engine to engine.

In-cylinder emission control techniques have been most effective in reducing the soot and fuel-derived SOF components of the particulate matter. As a result, the relative importance of the lube oil and sulfate components has increased. In many of today's development engines, the lubricating oil accounts for as much as 40 percent of the particulate matter, and the sulfates may account for another 25 percent. Lube oil emissions can be reduced by reducing oil consumption, but this may adversely affect engine durability. The only known way to reduce sulfate emissions is to reduce the sulfur content of diesel fuel.

The particulate SOF and gaseous hydrocarbons from diesel engines include many known or suspected carcinogens and other toxic air contaminants. These include polynuclear aromatic compounds (PNA) and nitroaromatics, formaldehyde and other oxygenated hydrocarbons. These last are also responsible for much of the characteristic diesel odor.

NO_x/Particulate Tradeoff--Diesel particulate and NO_x emissions result from the fundamental nature of the combustion process, making them especially difficult to control. As opposed to spark-ignition engines (which use a more-or-less homogeneous charge) all diesel engines rely on heterogeneous combustion. During the compression stroke, a diesel engine compresses only air. Fuel is injected into the combustion chamber in liquid form near the top of the compression stroke. The quantity of fuel injected with each stroke is determined by the engine power output required. After a brief period known as the ignition delay, the fuel is ignited by the hot air and burns. In the premixed burning phase, the fuel/air mixture formed during the ignition delay period burns rapidly. The subsequent rate of burning is controlled by the rate of mixing between the remaining fuel and air, with combustion always occurring at the interface between the two. Most of the fuel burned is burned in this diffusion burning stage, except under very light loads.

The fact that fuel and air must mix before burning means that a substantial amount of excess air is needed to ensure complete combustion of the fuel within the limited time allowed by the power stroke. Diesel engines, therefore, operate at overall air-fuel ratios which are considerably lean of stoichiometric. The air-fuel ratio during a given stroke is determined by the engine power requirements, which govern the amount of fuel injected (the amount of air is more or less constant, except in turbocharged engines). The minimum air-fuel ratio for complete combustion is about 21, corresponding to about 50 percent excess air. This ratio is known as the smoke limit, since smoke increases dramatically at ratios lower than this. The smoke limit establishes the maximum amount of fuel that can be burned per stroke, and thus the maximum power output of the engine.

The nature of the diesel combustion process ensures that both NO_x and soot will form. NO_x is primarily NO, which is formed at high temperatures close to the flame front in the presence of excess oxygen. Soot particles, on the other hand, are formed by the rapid polymerization of acetylene at moderately high temperatures under oxygen-deficient conditions. During diffusion burning, the local gas composition at the flame front is close to stoichiometric, with an oxygen-rich region on one side and a fuel-rich region on the other. The high temperatures and excess oxygen required for NO formation are thus always present on one side, and the moderately high temperatures and excess fuel required for soot formation are present on the other.

The rate of NO formation in diesels is a function of oxygen availability, and is exponentially dependent on the flame temperature. In diffusion burning, flame temperature depends only on the heating value of the fuel, the heat capacity of the reaction products and any inert gases present, and the starting temperature of the initial mixture. In the premixed burning stage, the local fuel-air ratio also affects the flame temperature, but this ratio varies from place to place in the cylinder and is very hard to control.

In the diesel engine, most of the NO_x emitted is formed early in the combustion process, when the piston is still near top-dead-center (TDC). This is when the temperature and pressure of the charge are greatest. Recent work by several manufacturers and consultants (Wade et al., 1987; Cartellieri and Wachter, 1987; mfrs. confidential data) indicates that most of this NO_x is actually formed during the premixed burning phase, and that reducing the amount of fuel burned in this phase can significantly reduce NO_x emissions. NO_x can also be reduced by actions which reduce the flame temperature during combustion. These actions include delaying combustion past TDC, cooling the air charge going into the cylinder, reducing the air-fuel mixing rate near TDC, and exhaust gas recirculation (EGR). Since combustion always occurs under near-stoichiometric conditions, reducing the flame temperature by "lean-burn" techniques, as in spark-ignition engines, is impractical.

Diesel soot is formed only during the diffusion burning phase of combustion. Most of the soot formed is subsequently burned during the later portions of the expansion stroke. Soot oxidation is much slower than soot formation, however, and the amount of soot oxidized is heavily dependent on the availability of high temperatures and adequate oxygen during the later stages of combustion. Actions which reduce the availability of oxygen (such as EGR, or operation at low air-fuel ratios), or which reduce the time available for soot oxidation (such as retarding the combustion timing or reducing the air-fuel mixing rate) tend to increase soot emissions.

Diesel HC emissions (as well as the unburned-fuel portions of the particulate SOF) occur primarily at light loads, as a result of excessive fuel-air mixing, which results produces a mixture too lean to burn. Other HC sources include fuel deposited on the combustion chamber walls by the injection process, fuel retained in the orifices of the injector which vaporizes late in combustion, and partly reacted mixture which is subjected to bulk quenching by too-rapid mixing with air. Advanced injection timing (especially at light loads and high speeds), higher bulk gas temperatures, and lower injection pressures tend to reduce HC emissions; high air swirl rates and high injection pressures tend to increase them.

It is apparent from the foregoing discussion that there is an inherent conflict between some of the most powerful diesel NO_x control techniques and particulate emissions. This is the basis for the much-discussed "tradeoff" relationship between diesel NO_x and particulate emissions. This "tradeoff" is not absolute--various NO_x control techniques have varying effects on soot and HC emissions, and the importance of these effects varies as a function of engine speed and load. These tradeoffs do place limits on the extent to which any one of these pollutants can be reduced, however. To minimize emissions of all three pollutants simultaneously requires careful optimization of the fuel injection, fuel-air mixing, and combustion processes over the full range of engine operating conditions.

Visible Smoke--Visible smoke is due primarily to the soot component of diesel particulate matter. Under most operating conditions, the exhaust plume from a properly adjusted diesel engine is normally invisible, with a total opacity (absorbance and reflectance) of two percent or less. Visible smoke emissions from heavy-duty diesels are typically due to operating at air-fuel ratios at or below the smoke limit, or to poor fuel-air mixing in the cylinder. Poor mixing may occur during "lug-down"--high-torque operation at low engine speeds, since turbocharger boost, air swirl level, and fuel injection pressure are typically poorer in these "off-design" conditions. Marginal air-fuel ratios also occur in full-power operation of naturally-aspirated engines, resulting in some visible smoke under these conditions.

In turbocharged engines, low air-fuel ratios can occur during transient accelerations, since the inertia of the turbocharger rotor means that the air supply during the first few seconds of a full-power acceleration is less than the air supply in steady-state operation. To overcome this problem, turbocharged engines in highway trucks incorporate an acceleration smoke limiter, which limits the fuel flow to the engine until the turbocharger has time to respond. The setting on this device must compromise between acceleration performance and low smoke emissions; presently, this compromise normally permits some visible smoke. The particulate reductions required to comply with the 1991 emissions standards are expected to essentially eliminate visible smoke emissions from properly functioning engines.

3.0 HEAVY-DUTY DIESEL EMISSIONS CONTROL: THE STATE OF THE ART

Under intense regulatory and market pressures, the technology for diesel emissions control has progressed rapidly in the 1980s. A recent report by one of the authors and others (Weaver et al., 1984) surveyed the then-current state of the art, but is already seriously out-of-date. The goal of this project was to update that previous report to reflect technical developments since 1984. This section summarizes the most significant such developments, and provides an overview of the state of the art of diesel emissions control in 1987.

In the course of this project, Radian staff met with representatives of every major U.S. manufacturer of heavy-duty diesel truck and bus engines to discuss the results of their R&D efforts and their progress toward compliance with the 1991 and 1994 emissions standards. Meetings were also held with most non-U.S. manufacturers selling heavy-duty diesel engines for on-highway use in the U.S. Further information was provided in confidential written materials submitted by nearly all manufacturers, in response to a Radian questionnaire. A copy of this questionaire is given in the Appendix. These data were supplemented by an intensive review of the applicable technical literature, including publications of the Society of Automotive Engineers (SAE), Federation Internationale des Societies des Ingenieurs de l'Automobile (FISITA), and other technical societies, EPA rulemaking dockets, and past technical reports by the authors and others.

Diesel engine emissions of NO_x, PM, and HC can be reduced by carefully tailoring the air induction, fuel injection, fuel-air mixing, and other elements of the combustion process. This <u>in-cylinder</u> emissions control is limited by the tradeoffs discussed in Section Two. Diesel emissions can also be reduced through <u>aftertreatment</u>--physical or chemical treatment of the exhaust gases after they leave the cylinder. Table 3-1 lists the significant emission control technologies in use or under development in each of these categories.

TABLE 3-1. TECHNIQUES FOR DIESEL ENGINE EMISSIONS CONTROL

IN-CYLINDER CONTROLS

Fuel Injection System
- Low sac/zero sac nozzles
- Retarded (fixed) injection timing
- Variable injection timing
- High injection pressure
- Transient smoke limiter
- Governor curve shaping
- Electronic fuel rate control
- Electronic injection timing control
- Reduced initial rate of injection
- Variable fuel injection rate

Air charging system
- Turbocharging
- Intercooling
  - Jacket Water
  - Air-air
  - Low flow air-water
  - Separate circuit air-water
- Low-inertia turbocharger
- Variable geometry turbocharger
- Externally-driven turbocharger
- Turbocompound engine
- Mechanical supercharger
- Gas-dynamic supercharger

Combustion Chamber
- Reduced crevice volume
- Optimized compression ratio
- Optimized air swirl ratio
- Variable air swirl ratio
- Re-entrant bowl combustion chamber
- Heat insulation
- Indirect injection
- Air cell

Reduced Oil Consumption

Exhaust Gas Recirculation

Continued

TABLE 3-1 (Continued)

AFTERTREATMENT CONTROLS

- <u>Trap-oxidizer Systems</u>
  - Traps
    - Cellular cordierite ceramic monolith
    - Cellular mullite fiber trap
    - Ceramic foam
    - Conductive SiC monolith
    - Woven silica-fiber "candle" trap
    - Precious metal catalyzed wire-mesh trap
  - Regeneration Techniques
    - Diesel fuel burner/bypass
    - Electric heater/bypass
    - Exhaust temperature increase
    - Catalyzed trap
    - Catalytic fuel additives
    - Catalyst injection in exhaust
    - Reverse flow/recycling
- <u>Catalytic Converters</u>
  - Cellular monolith
  - Pellet-type
- <u>Electrostatic Precipitator/agglomerator</u>
- <u>Selective Catalytic Reduction</u>
- <u>RapReNox Process</u>

The last few years have seen tremendous progress in the control of diesel engine emissions in the cylinder. As a result, it now appears likely that many engines, especially in the heavy-heavy class, may be able to comply with the "trap-forcing" 1991 emissions standards by in-cylinder means alone. If certification testing were conducted with low-sulfur fuel, most heavy-duty diesel engines would be able to meet the 1991 standards without the use of a trap, although some would require the use of a catalytic converter or other non-trap technique to reduce particulate emissions. These advances have also brought the 1994 particulate standards of 0.1 g/BHP-hr within the range of possibility, given an efficient trap and low-sulfur fuel.

In-cylinder emissions control--Recent progress in in-cylinder emissions control has been made possible, in large part, by improved understanding of the diesel combustion process, and of the factors affecting pollutant formation and destruction. Pollutant formation and destruction in the cylinder are determined by the specific course of the diesel combustion process. Modifying this process to minimize pollution involves a complex multi-dimensional tradeoff between NO_x, HC, and PM emissions, fuel economy, power output, smoke, cold-start ability, cost, and many other considerations. These changes go to the heart of diesel engine design, and they have the potential either to dramatically enhance or dramatically degrade an engine's performance relative to its competitors. As a result, engine manufacturers have devoted the bulk of their research and development resources to this area.

Most engine manufacturers have followed a broadly similar approach to in-cylinder control, although the specific techniques used differ considerably from one manufacturer to the next. This typical approach to in-cylinder emissions control includes the following major elements.

- Minimize parasitic HC and PM emissions (those not directly related to the combustion process) by minimizing nozzle sac volume and reducing oil consumption to the extent possible.

- Reduce PM emissions at constant NOx by refining the turbocharger/engine match and improving engine "breathing" characteristics. Many manufacturers are also experimenting with variable-geometry turbochargers to improve the turbocharger match over a wider speed range.

- Reduce PM and NO_x (with some penalty in HC) by cooling the compressed charge air as much as possible, via air-air or low-temperature air-water aftercoolers.

- Further reduce NO_x to meet regulatory targets by severely retarding fuel injection timing over most of the speed/load range. Minimize the adverse effects of retarded timing on smoke, starting, and light-load HC emissions via a flexible timing system to advance the timing under these conditions.

- Recover the PM increase due to retarded timing by increasing the fuel injection pressure and injection rate.

- Improve air utilization (and reduce PM emissions) by minimizing parasitic volumes such as piston/cylinder head clearance and piston top land volume.

- Optimize in-cylinder air motion through changes in combustion chamber geometry and intake air swirl to provide adequate mixing at low speeds (to minimize smoke and PM) without over-rapid mixing at high speeds (which would increase HC and NO_x).

- Control smoke and particulate emissions in full-power operation and transient accelerations through improved governor curve shaping and transient smoke limiting (generally through electronic governor controls).

In addition to these generally used approached, a number of other promising in-cylinder control techniques are under development by various manufacturers. These include variable air swirl devices for improved control of in-cylinder air motion over a range of speeds; fuel injection pumps with electronical control of the fuel injection rate; proprietary technology to minimize the initial fuel injection rate, thus reducing premixed burning and NO_x emissions; and innovative supercharging technologies to minimize or eliminate turbocharger lag. Turbocompound engines, which are being developed primarily for fuel economy reasons, will also help reduce emissions somewhat through increased engine efficiency.

It is striking that most of the in-cylinder emission reductions attained to date have come from painstaking optimization and incremental improvements to engine design, rather than from the application of major new technologies. Technologies such as electronic timing control and governing have played a fairly minor role in reducing emissions to date, although they have certainly helped to offset some of the deleterious effects of emissions control on engine performance.

Several technologies are also conspicuously absent from the list of those under development, due to their adverse effects on fuel economy or durability. The most significant of these are exhaust gas recirculation (EGR) and indirect injection. Properly modulated, EGR can significantly reduce NO_x emissions with a minimal increase in PM. Oil contamination and engine wear rates are increased by EGR, however, and manufacturers have been strongly resistant to its use. While relatively low in emissions, IDI engines are 5-10 percent less fuel efficient than DI engines, and are expected to lose market share as a result.

Aftertreatment control technologies--Potential exhaust aftertreatment technologies include trap-oxidizers, flow-through catalytic converters, and electrostatic precipitator/agglomerators. All of these would affect primarily particulate and HC emissions. Due to the oxidizing nature of diesel exhaust, aftertreatment techniques for NO_x require that a separate reducing agent be supplied. Despite considerable publicity given to one such system, this approach is considered infeasible for general application in vehicles.

Most of the research and development activity in diesel aftertreatment involves trap-oxidizers. A trap-oxidizer system consists of a durable particulate filter in the exhaust (the "trap"), along with some means of regenerating the filter by burning off ("oxidizing") the collected particulate matter. Development activity is concentrated on the "oxidizer" portion of the system, as suitable filter media have been available for some time.

Progress in trap-oxidizer development has been slower than anticipated. This is at least partly due to the limited resources being devoted to trap-oxidizer R&D. Most engine manufacturers are apparently pursuing a strategy of meeting the 1991 emissions standards by in-cylinder means alone, with trap-oxidizer development pursued only as a backup strategy and for meeting the 1994 standards. Trap-oxidizer development is thus "on the back burner" until the success or failure of the in-cylinder control strategy is determined.

Most of the manufacturers pursuing this strategy have chosen bypass-type trap-oxidizer systems using a cellular ceramic monolith trap and an electric heater or a diesel fuel burner as their primary development focus. This choice presents little technological risk, but the resulting trap-oxidizer systems are likely to be expensive and may not be reliable. Most of the manufacturers in this group are just arriving at the initial field testing stage in 1987; few have accumulated any significant operating time with traps on trucks in the field.

A few manufacturers appear to have devoted major efforts to trap-oxidizer system development. Foremost among these is Daimler-Benz, which has placed 50 prototype traps on buses operating in West Germany (Hardenberg, 1987). One other U.S. engine manufacturer has also devoted considerable effort to trap-oxidizer development, and has successfully accumulated more than 123,000 miles on a prototype system. The Daimler-Benz system uses a ceramic fiber coil trap, regenerated by injecting a catalyst solution into the exhaust. The U.S. manufacturer is using a catalyst-coated ceramic monolith, regenerated by modifying engine operating conditions. This approach is potentially much less costly and more reliable than the bypass/heater approach.

The success of in-cylinder particulate control efforts has led several manufacturers to investigate the feasibility of flow-through catalytic converters for reducing particulate emissions. Given the low engine-out particulate levels seen on current development engines, and the high organic content of the particulate matter, the use of a catalytic converter now appears as a possibly viable approach. By oxidizing much of the particulate SOF, a catalytic converter could reduce particulate emissions by 25 to 35 percent, which would be enough to meet the 1991 standard. A catalytic converter system would be much simpler and less expensive than a trap-oxidizer, since the flow-through design of the catalytic converter avoids the problem of regeneration. The major drawback to the catalytic converter approach is sulfate production—they would probably be feasible only with low-sulfur fuel.

Some researchers are also experimenting with electrostatic systems for particulate control; either alone or as part of an agglomerator/collector system. These efforts are still in the preliminary development stages.

Other issues--In the course of our research and discussions with diesel manufacturers, a number of regulatory issues surfaced which are related to the 1991 and 1994 emissions standards. These issues include diesel fuel sulfur and aromatic content, the desirability of reducing diesel HC and SOF emissions through an oxidation catalyst, and the related question of whether the 1994 particulate standard represents the best and most cost-effective means of achieving environmental goals. These issues are discussed in Section Seven.

<u>Lower NO_x standards</u>--There is presently no demonstrated technology for achieving heavy-duty diesel NO_x emissions levels less than about 4.5 g/BHP-hr without significant adverse effects on fuel economy and particulate emissions. There is some possibility that NO_x levels as low as 3.0 g/BHP-hr or lower might be achievable in the future, through the use of modulated EGR and reductions in premixed burning. These technologies will not be available before 1994 at the earliest, and government sponsorship of EGR research may be required. It is recommended that this issue be re-examined in about 1990.

4.0 PROGRESS IN IN-CYLINDER EMISSIONS CONTROL

The current state of the art in in-cylinder emissions control technology was briefly summarized in Section Three. This section provides a more detailed look at the individual technologies involved, focussing on significant recent developments in this area.

Diesel engine emissions are determined by the combustion process. This process is central to the operation of the diesel engine. Virtually every characteristic of the engine affects combustion in some way, and thus has some direct or indirect effect on emissions. As a result, the number of potential emission control techniques is very large. Synergism is also important--due to the interaction between different techniques, the effects of two or more techniques in combination may be greater or less than the sum of the effects of each one alone. To further complicate matters, the effects of changing any given characteristic may be different under different engine operating conditions.

The Heavy-Duty Transient Test Procedure involves engine operation over a wide range of engine speeds and loads, including idle and motoring (in which the engine is driven by the dynamometer, simulating engine braking in a vehicle). Different operating modes may differ greatly in their contribution to the overall emissions of different pollutants. Figures 4-1 through 4-3 are "maps" of total transient-cycle emissions as functions of speed and load for one heavy-duty diesel engine. Key features of these maps include the significant contribution of idle and light-load operation to total HC emissions, and the dominant effect of high-speed, part-to-full load operation on PM and NO_x. The fact that PM and NO_x are largely produced in the same operating modes limits the potential for reducing by "trading off" emissions in different modes.

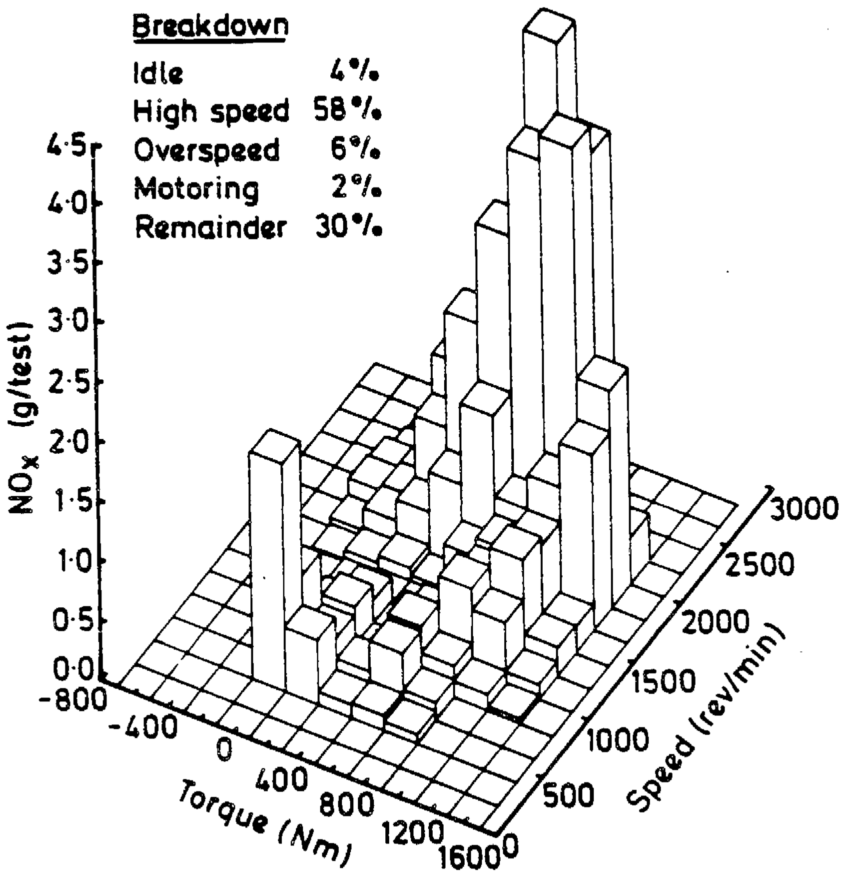


Figure 4-1. Integrated NO_x emissions from a heavy duty DI engine over the transient test cycle.

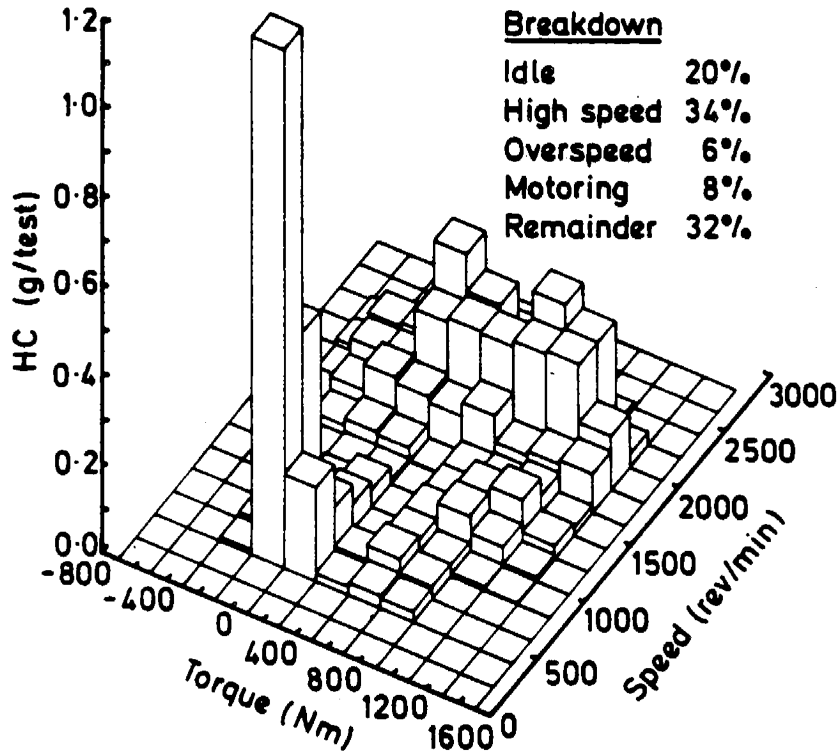


Figure 4-2. Integrated HC emissions from a heavy duty DI engine over the transient test cycle.

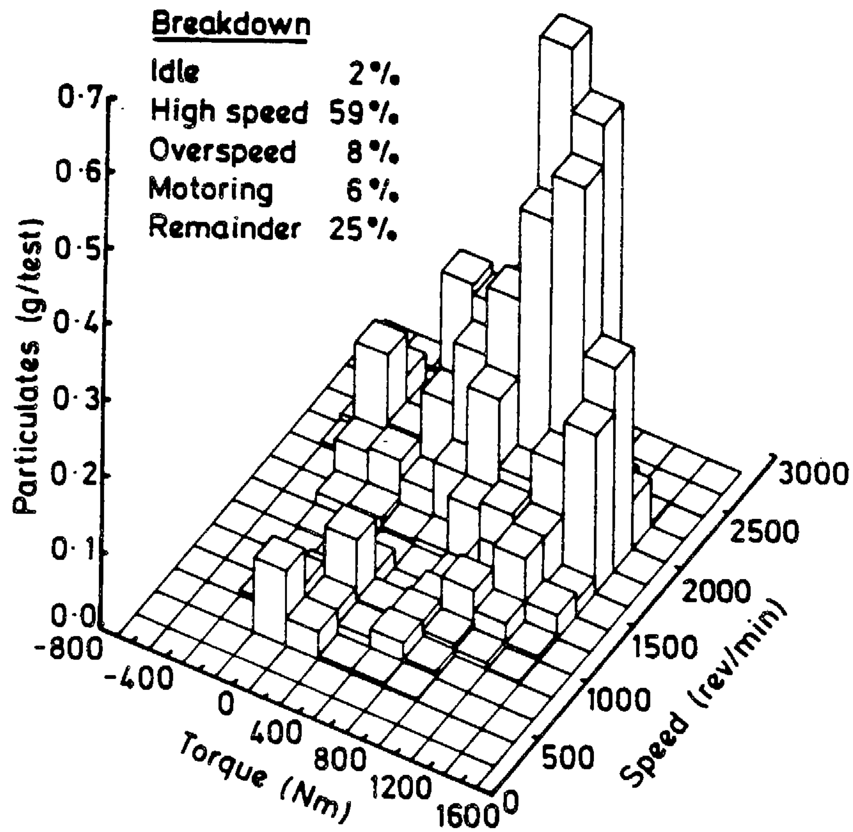


Figure 4-3. Integrated particulate emissions from a heavy duty DI engine over the transient test cycle.

4.1 Technology for In-Cylinder Emissions Control

Diesel combustion, and thus diesel emissions, are determined by the mixing of injected fuel and air in the combustion chamber. The engine systems which determine the rate, timing, and extent of this mixing and the amounts of air and fuel present thus largely determine the emission levels of the engine. The design of the fuel injection system, the air charging system, and the combustion chamber itself thus play major roles in in-cylinder control of diesel emissions. Most of the diesel emission control techniques now available or under development are concerned with modifications to one or more of these systems. These techniques are discussed in Sections 4.1.1 through 4.1.3 below.

Other approaches to diesel emission control include modifying the composition of the the air charge (e.g. by exhaust gas recirculation) or the fuel itself, and reducing lube-oil emissions by curbing oil consumption. Fuel modifications have been addressed extensively elsewhere (Weaver et al., 1985), and are briefly treated in Section Seven. Exhaust gas recirculation is discussed in Section 4.1.4 below, and oil consumption is treated in section 4.1.5.

4.1.1 Fuel Injection System

Key developments in fuel injection systems have been increased injection pressure, increasingly flexible control of injection timing, and more precise governing of the fuel quantity injected. Systems offering electronic control of fuel injection rate have also been introduced. Some manufacturers (as well as the consulting firm AVL) are also pursuing technology to reduce the amount of fuel burning in the premixed combustion phase to reduce noise and NO_x emissions. Other changes have been made to the injection nozzles themselves, to reduce or eliminate sac volume and to optimize the nozzle hole size, number of holes, and spray angle for minimum emissions.

Injection timing and governor controls--The effects of injection timing retardation vary with engine speed, load, and temperature. The optimal injection timing for a given set of emissions limits is thus a function of speed, load, and temperature as well. Many (but not all) engine manufacturers presently use mechanical systems to vary injection timing as a function of speed or load, but these systems have limited flexibility. In recent years, a number of microprocessor-controlled electromechanical fuel injection systems have been developed, and light-heavy and medium-heavy engines using such systems have been in production for several years.

The first heavy-heavy duty engines to utilize electronic timing control were the "DDECS" 8V-92 and Series 60 engines produced by Detroit Diesel-Allison (DDA) (Hames et al., 1985). Other manufacturers are following suit, however: Caterpillar has announced the limited availability of its PEEC system (Moncelle and Fortune, 1985) beginning in mid-1987. Virtually all manufacturers are developing such systems (or adapting vendor-supplied systems) in preparation for meeting the 1991 emissions standards.

By continuously adjusting the fuel injection timing to match a stored "map" of optimal timing vs. speed and load, an electronic timing control system can significantly improve on the NO_x/particulate and NO_x/fuel-economy tradeoffs possible with static or mechanically-variable injection timing. Most electronic control systems also incorporate the functions of the engine governor and the transient smoke limiter. This helps to reduce excess particulate emissions due to mechanical friction and lag-time during engine transients, while simultaneously improving engine performance. The potential emissions reductions with this approach have been documented by Wade and coworkers (1983). Other electronic control features, such as cruise control, upshift indication, and communication with an electronically-controlled transmission may also help to reduce fuel consumption and emissions levels, but these would not be reflected in the result of the Heavy Duty Transient Test.

<u>Fuel injection pressure and injection rate</u>--High fuel injection pressures are desirable in order improve fuel atomization and fuel-air mixing, and to offset the effects of retarded injection timing by increasing the injection rate. A number of manufacturers provided us with plots of PM and/or

smoke emissions vs. injection pressure, and all showed marked reductions as injection pressure was increased. High injection pressures are most important in low swirl DI engines, since the fuel injection system is responsible for most of the fuel-air mixing in these systems. For this reason, low swirl engines tend to use unit injector systems.

The injection pressures achievable in pump-line-nozzle fuel injection systems are limited by the mechanical strength of the pumps and fuel lines, as well as by pressure wave effects. Improvements in system design to minimize pressure wave effects, and increases in the size and mechanical strength of the lines and pumping elements have increased the injection pressures achievable in pump-line nozzle systems substantially. It now appears that a point of diminishing returns may have been reached in this area--further increases in injection pressure in some experimental systems have not greatly improved emissions.

The pumping elements in all current fuel injection systems are driven through fixed mechanical linkage from the engine crankshaft. This means that the pumping rate, and thus the injection pressure, are strong functions of engine speed. At high speeds, the pumping element moves rapidly, and injection pressures and injection rates are high. At lower speeds, however, the injection rate is proportionately lower, and injection pressure drops off rapidly. This can result in poor atomization and mixing at low speeds, and is a major cause of high smoke emissions during lugdown. Increasing the pumping rate to provide adequate pressure at low speeds is impractical, as this would exceed the system pressure limits at high speed.

A new type of in-line injection pump has recently been developed which provides a partial solution to this problem (Ishida et al., 1986). The cam driving the pumping elements in this pump has a non-uniform rise rate, so that pumping rate at any given time is a function of the cam angle. By electronically adjusting a spill sleeve, it is possible to select the portion of the cam's rotation during which fuel is injected, and thus to vary the injection rate. Injection timing varies at the same time, but the system is designed so that desired injection rate and injection timing correspond fairly well. Ishida and coworkers obtained a 25 percent reduction in PM emissions and a 10 percent reduction in HC using this system, with virtually no increase in NO_x.

The electronically variable injection rate technology has been developed primarily in Japan, and is being considered by several Japanese manufacturers. No U.S. manufacturers indicated that they were considering this system. It is worth noting that the same approach could easily be applied to a unit injector system using an electronically controlled spill valve, such as the Detroit-Diesel Allison DDECS system. Several other U.S. manufacturers are considering similar systems, so the variable-rate technology could readily be adapted if it were found desirable.

Initial injection rate and premixed burning--Recent work at Ford (Wade et al., 1987) and elsewhere has shown that a large fraction of the total NO_x formed is formed during the premixed combustion phase. This suggests that steps to reduce the amount of fuel burned in premixed combustion could significantly reduce total NO_x emissions. This could be achieved by reducing the initial rate of injection (RIRI). The overall rate of injection would need to be kept high, however, to avoid high PM emissions due to late burning. This requires varying the rate of injection during the injection stroke--a difficult mechanical problem.

Data from single-cylinder engine tests of a proprietary technology employing this approach were provided by one manufacturer. These data showed a nearly linear correlation between the amount of fuel injected prior to ignition and NO_x emissions. Using an (unspecified) proprietary technology, this manufacturer was able to reduce the initial fuel injection rate more than 60 percent, which resulted in more than a 50 percent reduction in NO_x emissions. This was achieved without significant adverse impacts on fuel consumption, HC, or PM emissions. As a side benefit, engine noise and maximum cylinder pressures were reduced as well. The manufacturer is now attempting to apply this technology to multicylinder engines, with a view to deployment by 1991.

Low sac/sacless nozzles--The nozzle sac is a small internal space in the tip of the injection nozzle. The nozzle orifices open into the sac, so that fuel flowing past the needle valve first enters the sac, and then sprays out the orifices. The small amount of fuel remaining in the sac tends to burn or evaporate late in the combustion cycle, resulting in significant PM and HC emissions. The sac volume can be minimized or even eliminated by redesigning the injector nozzle. One manufacturer reported nearly a 30 percent reduction in PM emissions through elimination of the nozzle sac. Fuel consumption was increased slightly, however.

Other problems such as inconsistent spray patterns and combustion gas intrusion into the injector have also been reported with sacless nozzles (Andoh and Shiraishi, 1986). These could possibly lead to an increased tendency toward nozzle deposits, and possibly higher deterioration factors in use.

4.1.2 Air Charging System

Increasing the air mass in the cylinder and reducing its temperature can reduce both NO_x and particulate emissions, as well as permitting greater fuel economy and more power output from a given engine displacement. Most heavy-duty diesel engines are presently equipped with turbochargers, and most of these have intercoolers. Virtually all engines will be equipped with these systems by 1991. Recent developments in air charging systems for diesel engines have been primarily concerned with increasing the turbocharger efficiency, operating range, and transient response characteristics; and with improved intercoolers to further reduce the temperature of the intake charge. Tuned intake air manifolds (including some with variable tuning) have also been developed, to maximize air intake efficiency in a given speed range. Turbocompound engines for line-haul trucks are also under development by several manufacturers: these will reduce emissions somewhat through improved fuel efficiency, and may also offer advantages for transient response.

Turbocharger refinements--Turbochargers for heavy-duty diesel engines are already highly developed, but efforts to improve their performance continue. The major areas of emphasis are improved matching of turbocharger response characteristics to engine requirements, improved transient response, and higher efficiencies. Engine/turbocharger matching is especially critical, because of the inherent conflict between the response charactistics of the two types of machines. Engine boost pressure requirements are greatest near the maximum torque speed, and most turbochargers are matched to give near-optimal performance at that point. At higher speeds, however, the exhaust flowrate is greater, and the turbine power output is correspondingly higher. Boost pressure under these circumstances can exceed the engine's design limits, and the excessive turbine backpressure increases fuel consumption. Thus, some compromise between adequate low-speed boost and excessive high-speed boost must be made.

Variable geometry turbochargers--Because of the inherent mismatch between engine response characteristics and those of a fixed-geometry turbocharger, a number of engine manufacturers are consider the use of variable geometry turbines instead (Wallace et al., 1986). In these systems, the turbine nozzles can be adjusted to vary the turbine pressure drop and power level in order to match the engine's boost pressure requirements. Thus, high boost pressures can be achieved at low engine speeds, without wasteful overboosting at high speed. The result is a substantial improvement in low-speed torque, transient response, and fuel economy, and a reduction in smoke, NO_x, and PM emissions.

Prototype variable geometry turbochargers have been available for some time, but they have not been used in production vehicles up to this point. The major reason for this is their cost, which could be as much as $1,000 more than a comparable fixed-geometry turbocharger. The need for a sophisticated electronic control system and concerns for the system's reliability have also deterred their use to date. With the forthcoming deployment of electronic engine controls on virtually all vehicles, these latter arguments have lost much of their force, and the fuel economy and performance advantages of the VGT are great enough to outweigh the costs in many applications. As a result, variable geometry turbochargers should be available on a number of production heavy-duty diesel engines in the relatively near future.

Other types of superchargers--A number of alternative forms of supercharging have been considered, with a view to overcoming the mismatch between turbocharger and engine response characteristics. The two leading candidates at present are the Brown-Bovari Comprex (tm) gas-dynamic supercharger, and mechanically-assisted turbochargers such as the "three-wheel" turbocharger developed by GM. The major advantages of these systems are superior low-speed performance and improved transient response. These advantages would be expected to yield some improvement in PM emissions, as well as driveability and torque rise. None of the manufacturers contacted reported any significant development efforts in this area, however.

Intercoolers--Most heavy-duty diesel manufacturers have either implemented low-temperature intercoolers already, or will implement them in time to comply with the 1988 emissions standards. The lowest charge air temperatures can be attained with air to air intercoolers, and these have been selected by the great majority of manufacturers. The major exception is Cummins, which has chosen to retain the basic water-air intercooler, but with drastically reduced radiator flowrates to reduce the water temperature.

Intake manifold tuning--Tuned intake manifolds have been used for many years to enhance airflow rates on high-performance gasoline engines, and are being considered for some heavy-duty diesel engines. A tuned manifold provides improved airflow and volumetric efficiency at speeds near its resonant frequency, at the cost of reduced volumetric efficiency at other speeds. At least one medium-heavy duty manufacturer is considering a variable-resonance manifold, in order to improve airflow characteristics at both low and high speeds.

Turbocompound engines--Several manufacturers are developing turbocompound engines for use in line-haul trucks (Holtman, 1987). The primary advantage of these engines is their increased fuel efficiency, due to their ability to extract work from some of the waste exhaust heat. Other things being equal, this should result in a small corresponding decrease in emissions. Another possible emissions-related advantage would be the potential to bypass the power recovery turbine at low engine speeds, thus increasing the pressure drop across the compressor turbine and thus providing more power to the compressor. This should markedly improve low-speed smoke emissions and transient response.

4.1.3 Combustion Chamber

Changes in the engine combustion chamber and related areas have demonstrated a major potential for emission control. Design changes to reduce the crevice volume in DI diesel cylinders increase the amount of air available in the combustion chamber. Changes in combustion chamber geometry--such as the use of a reentrant lip on the piston bowl--can markedly reduce emissions by improving air-fuel mixing and minimizing wall impingement by the fuel jet. Changing the compression ratio can have a marked effect on HC and PM emissions. Optimizing the intake port shape for best swirl characteristics has also yielded significant benefits. Several firms are considering variable swirl intake ports, to optimize swirl characteristics across a broader range of engine speeds. Ceramic components to reduce heat loss and protect critical parts from overheating are beginning to come into use, although the day of the "adiabatic" diesel engine has not yet come.

In addition to the common DI combustion systems, indirect-injection engines are still quite significant in the light-heavy duty market, although their continuing competitiveness beyond 1991 is questionable. Finally, air cells (small air chambers connected to the main combustion chamber by a narrow throat) have demonstrated significant particulate reductions in both DI and IDI engines.

Crevice volume--The crevice volume is that part of the compression volume which lies outside the combustion chamber. This included the clearance between the top of the piston and the cylinder head, and the "top land"--the space between the side of the piston and the cylinder wall above the top compression ring. The air in these volumes contributes little to the combustion process. The smaller the crevice volume, the larger the combustion chamber volume can be for a given compression ratio. Thus, reducing the crevice volume effectively increases the amount of air available for combustion.

The major approaches to reducing the crevice volume are to reduce the clearance between the piston and cylinder head through tighter production tolerances, and to move the top compression ring toward the top of the piston. This increases the working temperature of the top ring, and poses mechanical design problems for the piston top as well, but these problems have been addressed through redesign and the use of more expensive materials. The higher piston ring temperature also may also make additional demands on the oil.

Combustion chamber shape--Numerous test results indicate that, for high swirl DI engines, a reentrant combustion chamber shape (in which the lip of the combustion chamber protrudes beyond the walls of the bowl) provides a substantial improvement in performance and emissions over the previous straight-sided bowl designs. Researchers at AVL (Cartellieri and Wachter, 1987) found that the use of a reentrant bowl gave a 20 percent reduction in PM emissions from those measured with a straight-sided bowl at the same compression ratio. NO_x emissions were increased 3 percent, but the reentrant bowl combustion chamber is also more tolerant of retarded injection timing than the straight-sided bowl.

Because of the superiority of the reentrant bowl design for high-swirl engines, nearly all of the manufacturers of such engines are developing or already using this approach. Similar improvements in the performance of low-swirl DI engines may also be possible through modifications to combustion chamber geometry, but there is much less unanimity as to what the optimal shape may be. A number of different variations on the classic "mexican hat" combustion chamber shape have been tried, with some success.

Compression ratio--Most heavy-duty DI diesel engines presently have compression ratios in the range of 15 to 18, which has been found to give the optimal tradeoff between fuel economy and cold start ability. Higher compression ratios in the 19-20 range have been found to reduce HC and SOF emissions, and to increase the degree of injection timing retardation that can be tolerated without misfiring. Soot emissions tend to increase somewhat at higher compression ratios, since a larger fraction of the trapped air is then contained in the crevice volume. This effect can be minimized by minimizing crevice volumes, as discussed above.

Intake air swirl--Optimal matching of intake air swirl ratio with combustion chamber shape and other variables is critical for emissions control in high-swirl engines. The swirl ratio is the ratio of the rotational speed of the air charge in the cylinder to the rotational speed of the engine, which is determined by the design of the air intake port. Unfortunately, the selection of a fixed swirl ratio involves some tradeoffs between low-speed and high-speed performance. At low speeds, a higher swirl ratio provides better mixing, improving maximum torque and reducing smoke. However, this can result in too high a swirl ratio at higher speeds, impairing the airflow to the cylinder. Too high a swirl ratio can also increase HC emissions, especially at light loads.

Attaining an optimal swirl ratio is most difficult in smaller light-heavy and medium-heavy DI engines, as these experience a wider range of engine speeds than do heavy-heavy engines. One solution to this problem is to vary the swirl ratio as a function of engine speed. A two-position variable swirl system has been developed and applied to some diesel engines in Japan (Shimada et al, 1986). This system is being considered for engines used in the U.S. as well. Test data using this system show a marked effect on PM and NO_x emissions due to changes in the swirl ratio.

Heat insulation--Considerable effort is being devoted to the development of low heat rejection diesel engines. The major benefit of such engines would be the elimination of the engine cooling system, with its attendant power losses and reliability problems. Little information is available to assess the emissions impact of such engines, and the information which is available is contradictory. Overall, it appears that the technology of low heat rejection engines is too immature for any judgement to be made concerning its emission effects.

Indirect injection--Until recently, IDI engines were characterized by significantly lower NO_x and PM emissions than DI engines. Advances in DI engine technology have reduced this advantage, however, and it appears that DI engines now have the advantage in PM emissions. IDI engines retain some advantages in noise, volumetric power, and NO_x emissions, but suffer from higher fuel consumption and heat rejection rates. All light-duty and most light-heavy duty diesel engines in the U.S. at present are IDI models, but the trend is clearly toward small DI engines in the light-heavy duty class.

Air cells--An air cell is a small chamber connected to the main combustion chamber of the diesel engine by a narrow throat. It fills with high-pressure air during the compression stroke, then releases this air during the expansion stroke in a high-velocity jet. The increased oxygen supply and turbulence during the expansion stroke result in greater oxidation of the particulate material. A 41 percent reduction in FTP particulate emissions from an IDI engine has been reported (Wade et al., 1984). This was attained at the cost of a 3 percent increase in fuel consumption and NO_x emissions.

Although the air cell provided a significant improvement in PM emissions in this case, it is uncertain whether a similar improvement would be possible in a fully optimized engine. Air cells do not appear to be an area of active development--none of the manufacturers contacted mentioned any work in this area.

4.1.4 Exhaust Gas Recirculation

EGR is a time-proven NO_x control technique for light-duty gasoline and diesel vehicles, but has been little used in heavy-duty diesel engines. In heavy-duty diesel engines, EGR has been shown to increase wear rates and oil contamination, resulting in higher maintenance expenses and shorter engine life (Cadman and Johnson, 1986). For this reason, engine manufacturers have avoided using EGR, and little research on its effects has been performed. In the past, a few California-model medium-heavy engines used EGR to meet the California NO_x standard. Considerable adverse experience with these engines has reinforced the existing prejudice against EGR use in heavy-duty diesels.

Another reason for avoiding EGR is that is was considered to have little advantage over other NO_x control techniques such as retarding injection timing, at least in DI engines. Yu and Shahed (1981) found little difference in the NO_x/smoke tradeoff curves for EGR and for injection timing. EGR has a lesser impact on fuel economy than retarded timing (moderate EGR actually improves fuel economy slightly), but this has been outweighed by its adverse effects on durability. Only two of the manufacturers contacted in this study even mentioned EGR in their discussions of emission control techniques.

Some recent research results suggest that a re-evaluation of this technique may be in order, however. This research indicates that properly modulated EGR does not necessarily increase PM emissions significantly, even though NO_x may be dramatically reduced. EGR often (but not always) increases soot emissions, but gaseous HC and particulate SOF are generally reduced. In some cases, soot emissions may be reduced by EGR as well (Shiga et al., 1985). The effect of EGR on overall PM emissions may thus be positive or negative, depending on the specific operating mode.

An excellent example of EGR's potential as an emission control technique comes from some work performed at Ford (Wade et al., 1985). The Ford researchers developed three small prototype high-speed DI diesel engines suitable for passenger car service. The overall combustion systems in these engines closely resembled those of many small-bore, high-swirl light-heavy and medium-heavy duty engines which are now coming into use. The engines were extensively optimized for minimum emissions, with features such as reentrant bowl combustion chambers, tuned intake manifolds, and optimized compression ratios.

EGR rates applied to these engines ranged from 52 percent at idle down to zero at 75 percent load. The EGR schedules were selected on the basis of engine mapping tests to optimize fuel consumption while meeting the particulate requirements. As a result of the EGR application, NO_x emissions from the largest of the three engines were reduced more than 50 percent, from 4.8 g/BHP-hr to less than 2.0 g/BHP-hr, measured on an engine test cycle simulating the Federal light-duty test procedure. NO_x emissions from the two smaller engines were reduced even more: from 7 g/BHP-hr to around 3.0. Particulate emissions from these engines were about 0.5 to 0.6 g/BHP-hr, measured over the light-duty FTP cycle. Particulate emissions from the smaller engines with EGR were comparable to those from similar light-duty IDI engines without EGR.

These results cannot be translated directly to heavy-duty engines, due to the differences in emission test cycles between the light-duty FTP and the Heavy-Duty Transient Test procedure. Compared to the light-duty cycle, the heavy-duty procedure involves much more high-power operation, which would limit amount of EGR that could be tolerated. Nonetheless, these data strongly suggest that the properly modulated EGR could result in a <u>major</u> reduction in NO_x emissions, with minimal impacts on PM, fuel economy, or driveability.

To obtain a rough quantification of the potential impact of EGR in a heavy-duty engine, we developed a simple model of EGR effects. Modal emissions data for a modern low-emission heavy-duty engine were taken from the work of AVL (Cartellieri and Wachter, 1987). These data included weighted NO_x and particulate emissions in g/BHP-hr for each of 14 operating modes selected to represent key portions of the heavy-duty transient cycle. Particulate emissions data were further divided into fuel-derived HC, lubricant-derived HC, and insoluble (soot) components. The sum of the weighted emissions from these 14 steady-state modes was shown by the AVL researchers to closely approximate the transient cycle results.

The effects of EGR on transient cycle emissions for the AVL engine were estimated by assigning an EGR rate to each operating mode, then estimating the resultant effects on soot, SOF, and NO_x emissions, based on the data provided by Wade and coworkers (1985). Assigned EGR rates were inversely proportional to engine load, and ranged from 40 percent EGR at zero load to 0 percent at full load. The results of this calculation showed a 27 percent reduction in NO_x emissions (from 6.0 to 4.3 g/BHP-hr, at the cost of a 14 percent increase in PM) (from 0.242 to 0.276 g/BHP-hr). Although very rough, these results may be considered as an approximate indicator of EGR's potential for heavy-duty diesel engines. Compared to the effects of injection timing retard at similar NO_x levels, the tradeoff ratio of 1.7 g/BHP-hr NO_x reduction to 0.034 g/BHP-hr PM increase is an extremely favorable one.

4.1.5 Oil Consumption

A significant fraction of diesel particulate matter consists of oil-derived hydrocarbons and related solid matter. The long-chain (typically 20-carbon) hydrocarbons in the oil readily condense to form liquid particles in the dilute exhaust, and are collected on the particulate filter. A number of researchers (and many of the manufacturers interviewed in this study) have estimated the oil contribution to particulate emissions by assigning all of the heavy-hydrocarbon fraction of the SOF to the oil. Estimates of the oil contribution to overall PM emissions by this means range from 10 to 50 percent (Cuthbertson et al, 1987; Cartellieri and Wachter (1987), Hales and May, 1986; mfrs. confidential data).

Estimates of the oil contribution based on molecular weights may be significantly too high, since they ignore the possible contribution pyrosynthesized hydrocarbons, as well as heavy ends from the fuel. Pyrosynthesis of polynuclear aromatic hydrocarbons (probably by the same processes which produce soot) has been demonstrated (Williams et al., 1987). Measurements using a radioactive tracer technique showed a somewhat smaller contribution by the lube oil.

In addition to the direct lube oil contribution to particulate emissions, ash-forming oil additives could pose a significant durability problem for particulate traps. These additives include zinc dithiophosphate for wear protection and overbased calcium and magnesium sulfonates to prevent the acid gases (SO_x and NO_x) from the combustion process from corroding the engine. The ash from these additives amounts to about one to two percent of the mass of oil consumed. This ash would be collected by a trap-oxidizer, and--being noncombustible--would accumulate and gradually plug it.

Reduced oil consumption has been a design goal of heavy-duty diesel engine manufacturers for some time, and the current generation of diesel engines already use fairly little. Further reductions in oil consumption are possible through careful attention to cylinder bore roundness and surface finish, optimization of piston ring tension and shape, and attention to valve stem seals, turbocharger oil seals, and other possible sources of oil loss. Some oil consumption is required, however, in order for the oil to perform its lubricating and corrosion-protective functions.

Some manufacturers have measured emissions from engines modified for ultra-low oil consumption. Oil consumption in each case was reduced to an extent that was expected to result in unacceptable long-term durability. These tests have shown a reduction of 0.07 to 0.10 g/BHP-hr in particulate matter due to the reduced oil consumption.

4.2 Achievements in In-Cylinder Emissions Control

Figure 4-4 shows the NO_x/PM emissions tradeoff projected by Weaver et al. in 1984, compared to the results from current development engines for a number of engine manufacturers. The lowest transient emissions results to date, however, have been reported by the Austrian engine consulting firm of AVL, in a project documented by Cartellieri and Wachter (1987). These showed emissions of 4.5 g/BHP-hr NO_x and 0.23 g/BHP-hr PM using EPA certification fuel. This value is within the "box" of the 1991 standards, but it does not provide sufficient margin to ensure compliance for PM. To ensure adequate margin for compliance, manufacturers generally felt they would require low-mileage PM levels in their development engines no higher than 0.17 to 0.20 g/BHP-hr.

As Figure 4-4 shows, at least one U.S. manufacturer has nearly equalled the AVL results in its engine development work, while several others have generated results only slightly worse. All of these data are for current development engines, and none of these engines was considered to be fully developed by its manufacturer. None of them, for instance, incorporated any extraordinary measures to reduce lube-oil consumption, and none included a variable-geometry turbocharger. It appears likely that the incorporation of such additional measures into the emissions control package could bring many, if not most, of the manufacturers within reasonable range of their targets for compliance with the 1991 standards, even using the present (0.3 percent sulfur) certification fuel.

Actual compliance is by no means certain, however. A key remaining question concerns the emissions deterioration rates (especially for PM) at these very low emissions levels. Few manufacturers have accumulated any significant durability data on these ultra-low emission engine configurations, and one manufacturer which had done so indicated that the deterioration factors had been significantly higher than expected. Until more durability data are available on these engines, this will remain an open question.

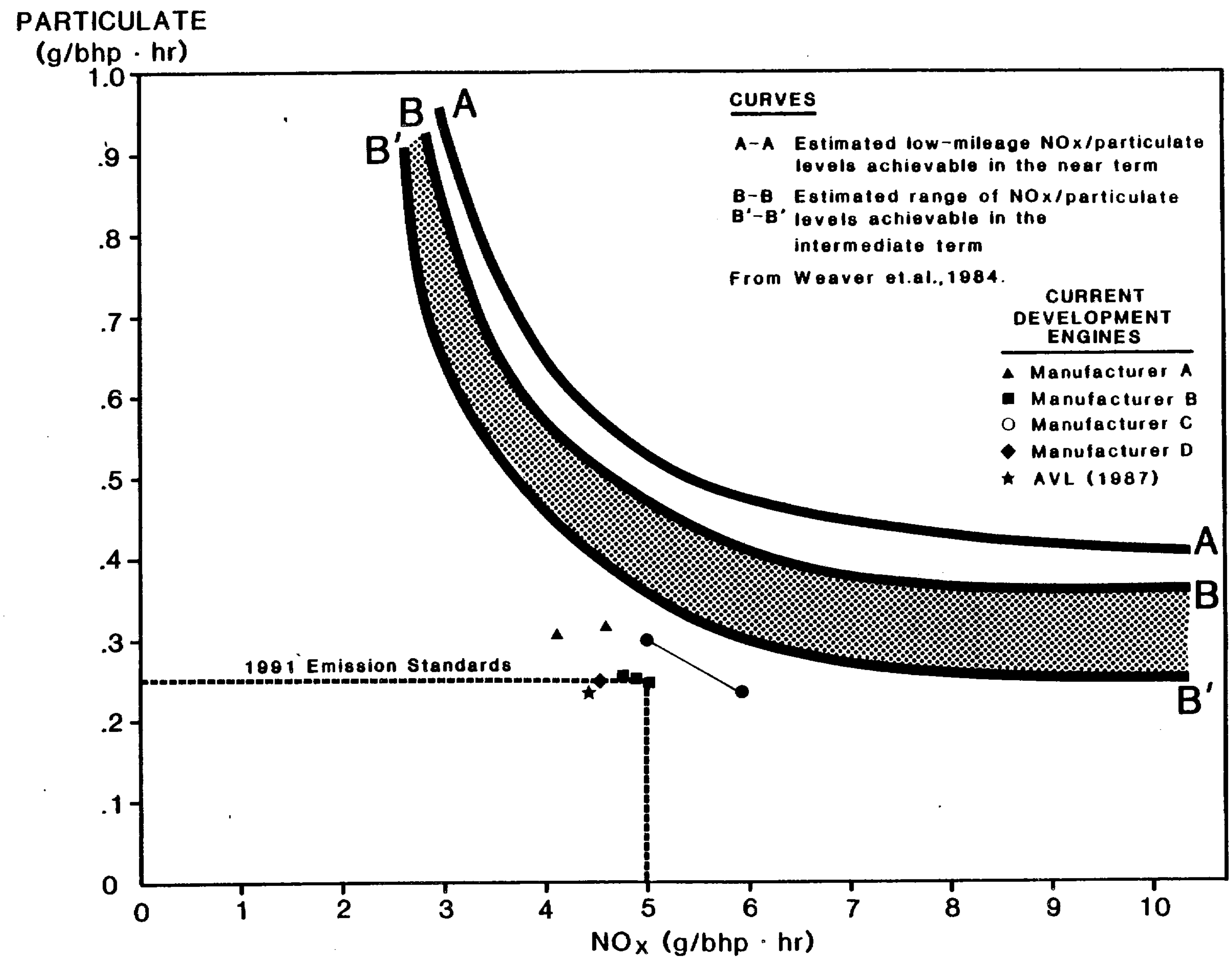


Figure 4-4. Diesel NO_x/Particulate Trade Off - Current Development Results vs. 1984 Projections.

5.0 PROGRESS IN TRAP-OXIDIZER TECHNOLOGY

A trap-oxidizer system consists of a durable particulate filter (the "trap" positioned in the engine exhaust, along with some means for cleaning the filter by burning off ("oxidizing") the collected particulate matter. Trap-oxidizer technology and its application to light-duty and heavy-duty vehicles have been discussed extensively in previous reports by one of the authors and other workers (Weaver, 1983, 1984; Weaver et al., 1984). This section updates those earlier discussions to reflect recent technological developments and trends in trap-oxidizer technology.

The construction of a filter capable of collecting diesel soot and other particulate matter from the exhaust stream is a straightforward task, and a number of effective trapping media have been developed. The great problem of trap-oxidizer system development has always been with the process of "regenerating" the filter by burning off the accumulated particulate matter.

As discussed in Section 2.3, diesel particulate matter consists primarily of a mixture of solid carbon coated with heavy hydrocarbons. The ignition temperature of this mixture is above the normal range of diesel engine exhaust temperatures, so that special means are needed to assure regeneration. Once ignited, however, this material can produce very high temperatures, which can easily melt or crack the particulate filter. Initiating and controlling the regeneration process to ensure reliable regeneration without damage to the trap is the central engineering problem of trap-oxidizer development.

Compared to the in-cylinder emission control technologies discussed in the preceding section, trap-oxidizer technology has progressed more slowly and in a more predictable manner since 1984. This is partly due to the simpler and more predictable physical and chemical phenomena involved, and partly due to the much lower priority accorded it in most manufacturers' research and development efforts. Despite the relatively slow general rate of progress, several manufacturers have fielded successful prototype trap-oxidizer systems, and it appears that the technology will be available, if needed, in 1991. However, the fact that most manufacturers have been slow to proceed to field testing may result in inadequately tested systems being marketed. These could possibly prove very damaging, as the widely publicized failure of a few such systems could affect public perception of all trap-oxidizers, and result in widespread tampering and removal.

5.1 Traps

The different types of particulate traps were reviewed in considerable detail by Weaver et al. in 1984. There have been relatively few new developments in this area since that time. One new development which has occurred is the introduction of an electrically conductive silicon carbide trap by Fogarty Corporation in Britain. Performance data for this trap have not yet been published, however. In addition, some additional performance data have become available for cellular mullite fiber traps (Simon et al., 1986; Mihara et al., 1986) and for the ceramic-fiber coil traps used by Daimler-Benz (Hardenberg et al., 1987a). Improvements in materials and mounting techniques have reduced the problem of cracking due to thermal stress in ceramic monolith traps. Finally, a number of reports documenting decidedly mixed results in field tests of the Johnson-Matthey catalytic wire mesh trap have cast serious doubt on the viability of this approach.

Cellular Cordierite ceramic monolith trap--Presently, as in 1984, most of the trap-oxidizer systems under development are based on the cellular cordierite ceramic monolith traps produced by Corning Glassworks and NGK-Locke. These traps can be formulated to be highly efficient (collecting essentially all of the soot, and a large fraction of the particulate SOF), and they are relatively compact, having a large surface area per unit of volume. Because of their relatively simple production process, they could also be produced fairly inexpensively. They are also readily coated or impregnated with catalyst material to assist regeneration. However, the high concentration of soot per unit of volume makes these traps rather sensitive to regeneration conditions.

Trap loading, temperature, and gas flow rates must be maintained within a fairly narrow window. Otherwise, the trap fails to regenerate fully, or cracks or melts due to overheating.

The incidence of thermal stress cracking in cordierite monolith traps has been reduced by recent improvements in materials and mounting techniques, but trap melting due to uncontrolled regeneration remains a problem. Melting typically occurs in the center of the downstream end of the trap. Since particulate combustion generally begins at the upstream face of the trap, the downstream end is preheated by the burning of the particulate upstream. This increases both the starting temperature of the downstream end and the particulate burning rate, and leads to very high temperatures.

With a non-catalyzed trap, there is a fairly narrow range of trap loadings within which regeneration can be undertaken successfully. If the particulate loading on the trap is too low, combustion will not propagate well and regeneration will be incomplete. If too high, the trap will melt. Controlling the regeneration process so that the trap loading will always be within this range is a very difficult proposition, and manufacturers reported many trap failures in development and testing.

This problem can be alleviated in several ways. One approach is to reduce the length of the trap (increasing its width to keep the filtering surface the same), thus reducing the temperature increase at the rear. This can lead to packaging problems, however. Another approach is to add a catalyst coating to the trap, reducing the regeneration temperature and the minimum loading required for regeneration. The latter approach has several other advantages, as discussed in the next section.

Until recently, ceramic monolith traps could be produced only in relatively small diameters (five to six inches), due to the limitations of the extrusion process used to form them. Larger traps had to be formed by cementing together a number of individually-extruded sections--a very expensive process. Monolith traps are becoming available in larger sizes as problems of extrusion technology are resolved, however. Trap manufacturers have indicated that trap diameters of eight to nine inches are now feasible for production, and one (NGK) displayed a trap of approximately 11 inches diameter at the 1987 SAE exposition. One of this size of trap would be sufficient for most medium-heavy and heavy-heavy duty trucks.

Cellular Mullite fiber traps--Compared to the cordierite monolith traps discussed above, Mullite fiber traps have somewhat lower efficiency and lower mechanical strength, are much more resistant to thermal cracking, and may be easier to fabricate in large sizes.

Mullite fiber traps are similar in principle to the cordierite monolith traps, but are constructed by a different method. In one approach, a felt of green (unfired) mullite fibers is corrugated to produce a flat cellular sheet similar to a the corrugated cardboard used in paper boxes. This sheet is then wound into a round or oval shape and fired (Mihara et al., 1986). Figure 5-1 shows a trap of this type. Large traps could be produced quite easily using this process.

In an alternative approach, porous blocks of mullite fibers were fired, and then holes were drilled from each side to form the cellular structure (Simon et al, 1986). This resulted in a shorter, wider trap, reducing the problem of melting at the end of the trap. This process is quite expensive, however, due to the large number of drill holes required.

Because of their felt-like structure, Mullite fiber traps could be expected to gradually shed small ceramic fibers when subjected to repeated thermal cycling and/or exhaust pulsations. They would therefore be unsuitable for installation upstream of a turbocharger. Long-term degradation in efficiency and structural integrity would also be possible concerns. Durability data with these traps are very limited, so the extent to which these problems will be encountered in practice is unknown.

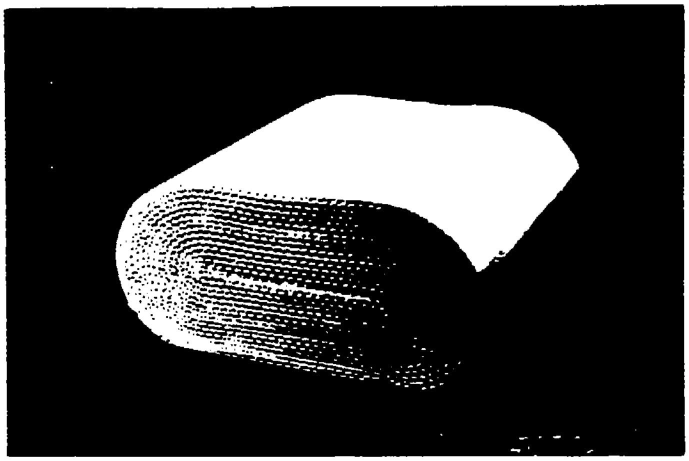


Figure 5-1a. Wound oval trap.
(Source: Ise et al., 1986.)

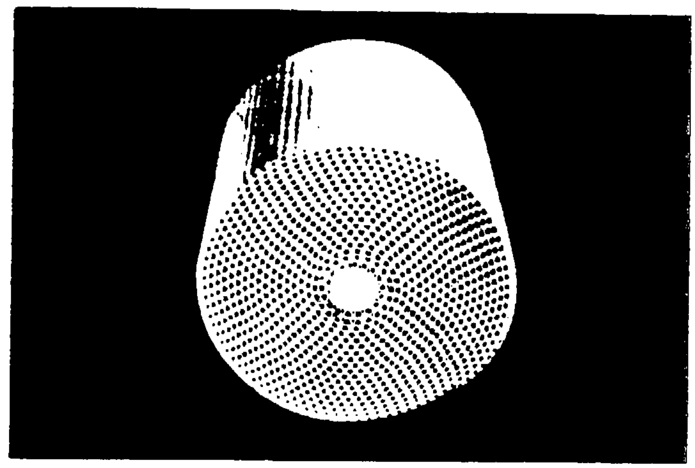


Figure 5-1b. Wound round trap.
(Source: Ise et al., 1986.)

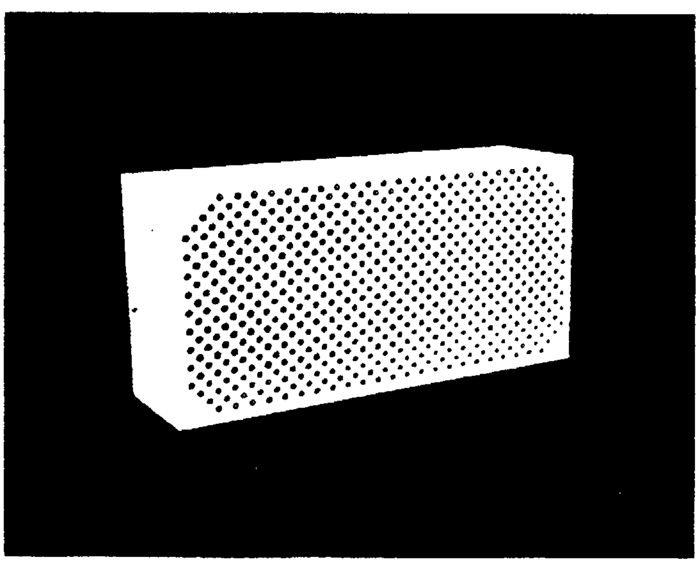


Figure 5-1c. Trap machined from fiber block.
(Source: Simon et al., 1986.)

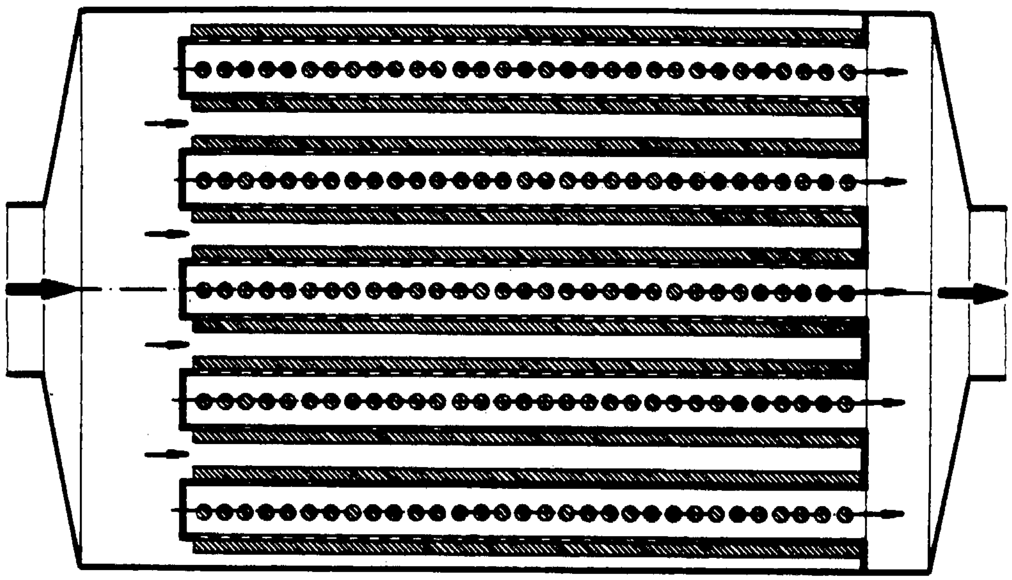
Figure 5-1. Types of Mullite Fiber Traps.

Ceramic fiber coil traps--These traps are composed of a number of individual filtering elements, each of which consists of a number of thicknesses of silica-fiber yarn wound on a punched metal support. This type of trap was referred to as the "candle" trap in previous reports, due to the appearance of the filtering elements. A number of these filtering elements are suspended inside a large metal can to make up a trap. Figure 5-2 is a schematic diagram of this system.

The advantages of the ceramic fiber coil trap include high filtering efficiency and immunity to thermal cracking. In addition, its low ratio of filtering area to volume (which results in a low volumetric soot loading) and the heat capacity and thermal conductivity of the materials make this trap nearly impossible to melt. Its primary disadvantages are the relatively large volume required and a fairly rapid increase in backpressure with increasing particulate loading. The silica yarn coils can also be mechanically cut or frayed by sharp objects, or loosened by repeated thermal cycling (Hardenberg et al, 1987a). The trap is also relatively complex structurally--implying that it could be expensive to manufacture.

Daimler-Benz has deployed prototype traps of this design in more than 50 city buses in West Germany (Hardenberg, 1987). To allow for interchangeability, these traps were constrained to be the same size as the normal muffler--severely limiting the volume available. Despite this constraint, trap performance has been good so far.

Johnson-Matthey catalyzed wire-mesh CTO (tm)--1986 saw the publication of results from a number of demonstration programs using the Johnson-Matthey CTO system on city buses. These included programs in the United Kingdom (Hickman and Jaffray, 1986), the Netherlands (Rijkeboer et al., 1986); Southern California (Pellegrin, 1986; Ullman, 1986); Philadelphia (McCormick et al., 1986); and Phoenix (Newman and Enga, 1986). Of these, only the Philadelphia demonstration could be considered an unqualified success. The Phoenix program suffered a series of regeneration failures before ultimately achieving



(Source: Hardenberg et al., 1987.)

Figure 5-2. Ceramic Fiber Coil Trap (Schematic).

RADIAN CORPORATION

a durable trap, and Southern California program suffered from a series of trap and engine mechanical failures. Both of the European programs resulted in trap failures in service.

The numerous failures in demonstration programs using this system, the continuing problem of sulfate emissions due to the precious-metal catalyst, and the relatively low trapping efficiency of the CTO have cast doubt on the viability of this approach. None of the engine manufacturers contacted considered it their primary approach, and many had abandoned development of it due to repeated failures. While some successes have been demonstrated as well, it remains to be seen whether the persistent problems that have plagued this system can be overcome.

Fogarty electrically conductive ceramic traps--A novel trap-oxidizer system based on electrically conductive ceramics has been proposed by Fogarty Corporation in the U.K. This system uses a set of hollow porous silicon carbide cylinders--similar to the "candles" in the Daimler-Benz system--as the trapping elements. Regeneration is provided by electric heating, using the conductive filter elements themselves as the heating elements. While this approach has obvious advantages, little information on the system's performance is available.

5.2 Regeneration techniques and systems

Numerous techniques for regenerating particulate trap-oxidizers have been proposed, and a great deal of development work has been invested in many of these. These approaches can generally be divided into two groups: passive systems and active systems. Active systems can be further divided into in-line regeneration systems and bypass systems. All passive systems and many active systems rely on catalyst coated traps and/or catalytic additives to initiate or promote regeneration.

Passive vs. active regeneration systems--Passive systems rely on attaining the conditions required for regeneration as a result of the normal operation of the vehicle. This requires the use of a catalyst (either as a coating on the trap or as a fuel additive) in order to reduce the ignition temperature of the collected particulate matter. Active systems, on the other hand, monitor the buildup of particulate matter in the trap and trigger specific actions intended to regenerate it when needed. A wide variety of approaches to triggering regeneration have been proposed, from diesel fuel burners and electric heaters to catalyst injection systems.

Passive regeneration systems face special problems on heavy-duty vehicles. Regeneration temperatures must be attained in normal operation, even under lightly loaded conditions. Because of the variability in their loading and use patterns, trucks may sometimes operate for long periods at very light loads. Exhaust temperatures from heavy-duty diesel engines are already fairly low, and recent developments such as air to air intercooling and increased turbocharger efficiency are reducing them still further. Existing catalyst coatings cannot ensure trap regeneration under all conceivable operating conditions.

The most promising passive system from a regeneration standpoint is the use of catalytic fuel additives. Some test trucks have accumulated substantial mileages using additives, and have demonstrated essentially continuous regeneration. A number of effective additive systems have been developed, using copper, manganese, lead, and cerium (Simon and Stark, 1985; Rao et al., 1985). These additives are capable of promoting regeneration at relatively low temperatures--one system demonstrated regenerate even in continuous idling (Ise et al., 1986). Manufacturers are reluctant to use the additive system, however, due to the problems of additive supply, reduced trap durability due to plugging, and uncertainty as to the future regulatory status of this approach.

Presently, no purely passive systems appear to be under serious consideration for heavy-duty applications, although some research is still being devoted to them. The major emphasis, therefore, is on active regeneration systems. Some manufacturers are also working on quasi-passive systems, in which the system will usually regenerate passively without intervention, but the active regeneration system remains as a backup. This is a desirable arrangement, since the energy costs of regeneration would be much lower, and the passive element would provide some insurance against the failure of the active system.

All active and quasi-passive regeneration systems require some means of monitoring trap loading in order to trigger regeneration at the proper time. The only practical measure of trap loading is the pressure drop across the trap. The long-term durability of sensors to measure this pressure drop remains a concern, however. Problems due to particulate fouling, heat and vibration damage, and even accidental disconnection have been reported in test programs. These problems could be expected to be even more significant on vehicles in use.

In-line vs. bypass systems--Active regeneration systems can be classified as either in-line or bypass-type systems. In the in-line system, exhaust continues to flow through the trap during regeneration, while with the bypass system the exhaust is bypassed around the trap. Some bypass systems involve a dual-trap design, with the exhaust being routed through one trap while the other is regenerated. Most systems under development include only a single trap, however, and route the raw exhaust to the atmosphere during regeneration. These systems raise serious concerns over tampering and I/M enforcement problems.

The exhaust stream from a vehicle engine varies rapidly and unpredictably in both temperature and flowrate, depending on the demands of the driving cycle. This variability would pose impossible control problems for systems such as diesel fuel burners and electric heaters. The need to heat the entire exhaust stream would also be very wasteful of energy, and would be well beyond the capacity of a truck's electrical system. For these reasons, burner and electric heater-based regeneration systems usually bypass the exhaust around the trap during regeneration. Combustion air for regeneration is supplied either by a separate air pump, or by admitting a small amount of exhaust into the trap.

For cost and compactness reasons, nearly all manufacturers using these systems intend to use only a single trap, routing the unfiltered exhaust to the atmosphere during regeneration. Unfortunately, such systems are virtually an open invitation to tampering. A bypass system requires one or more automatically-actuated valves in the exhaust system to close off the trap and open the bypass. Tampering with this valve to bypass the trap continuously would be a trivial matter--similar to the ease of tampering with EGR valves on light-duty gasoline vehicles. The motivations for tampering with trap-oxidizer systems, and the likely incidence of such tampering, have been discussed at length elsewhere (Weaver and Klausmeier, 1987a).

By so tampering, a truck owner could eliminate nearly all the real or perceived disadvantages of the trap-oxidizer system: fuel loss, power loss, maintenance requirements, and potential safety problems. Furthermore, this tampering would be reversible--making it unlikely to be detected in a periodic I/M program. Even random anti-tampering inspections would be poor deterrents. As a matter of good engineering practice, bypass valves would probably be designed to fail in the bypassed position (since failing in the other position would overload the trap, and possibly cause a destructive fire). It could thus be difficult to prove that the valve had been tampered with deliberately.

Catalytic coatings--Engine and catalyst manufacturers have experimented with a wide variety of catalytic material and treatments to assist in trap regeneration. Good results have been obtained both with precious metals (platinum, palladium, rhodium, silver) and with base metal catalysts such as vanadium and copper. Precious metal catalysts are effective in oxidizing gaseous HC and CO, as well as the particulate SOF, but are relatively ineffective at promoting soot oxidation. Unfortunately, these metals also promote the oxidation of NO in the exhaust to the more toxic NO_2, and of SO_2 to particulate sulfates such as sulfuric acid (H_2SO_4). The base-metal catalysts, in contrast, are effective in promoting soot oxidation, but have little effect on HC, CO, NO, or SO_2.

Catalyst manufacturers have attempted to reduce the sulfate-forming tendencies of the precious metal coatings by changes in the catalyst and washcoat formulation. The fraction of sulfur converted to SO_2 has been reduced from 25-60 percent to 2-10 percent by these changes. Unfortunately, these changes also seem to reduce the catalyst's HC and CO oxidation activity. The resulting catalysts, while producing acceptably low sulfate levels, are only marginally satisfactory for promoting regeneration. This dilemma could be greatly alleviated through the use of low sulfur fuel.

Base metal coatings capable of reducing trap regeneration temperatures to 380-400°C have been demonstrated (Engler et al., 1986). This is about 150°C less than would be required without the catalyst. However, the best results to date have been attained with a combination of base and precious metal coatings, with the base metal coated on the upstream (sooty) side of the trap walls, and the precious metal on the downstream (clean) side. The extra heat generated by the HC and CO oxidation on the precious-metal catalyst apparently contributes to the soot combustion, reducing the regeneration temperature by about 25°C (Engler et al., 1986).

Sulfate production in these tests was relatively low, and was outweighed by the reduction in particulate SOF getting through the trap, so that the addition of the precious metal catalyst gave a small reduction in PM emissions as well. HC and CO conversion efficiencies were relatively low--40 to 50 percent for HC and 45 to 80 percent for CO. This was presumably due to the reduction in catalyst activity needed to control sulfate emissions.

To date, no catalytic coating has sufficiently reduced the trap regeneration temperature to permit reliable passive regeneration in heavy-duty diesel service. Catalyst performance is limited by sulfate production with current fuels--therefore, improved performance could be expected with low sulfur fuel. It is unlikely, however, that this improved performance would be sufficient by itself to allow purely passive operation.

Catalyst coatings also have a number of advantages in active systems, however. The reduced ignition temperature and increased combustion rate due to the catalyst mean that less energy is needed from the regeneration system. Regeneration will also occur spontaneously under most duty cycles, greatly reducing the number of times the regeneration system must operate. The spontaneous regeneration capability also provides some insurance against a regeneration system failure. Finally, the use of a catalyst may make possible a simpler regeneration system.

Although normal heavy-duty diesel exhaust temperatures are not high enough to provide reliable regeneration for a catalyst-coated trap, the exhaust temperature can readily be increased by changes in engine operating parameters. Retarding the injection timing, bypassing the intercooler, throttling the intake air (or cutting back on a VGT), and/or increasing the EGR rate markedly increase the exhaust temperature. Applying these measures all the time would seriously degrade fuel economy, engine durability, and performance. The presence of an electronic control system, however, would make it possible to apply them <u>briefly</u>, and only when needed to regenerate the trap. Since they would be needed only at light loads, the effects on durability and performance would be imperceptible.

One engine manufacturer has successfully accumulated more than 120,000 miles on a prototype system of this type. This approach is simpler and potentially much more reliable than the bypass-type systems being developed by most manufacturers.

Precious metal catalysts also have important advantages from an environmental standpoint. In addition to oxidizing gases HC and CO and particulate SOF, these catalysts can dramatically decrease emissions of PAH, nitro-PAH, aldehydes, and other air toxics (Andrews et al., 1987; Hunter et al., 1981), as well as diesel odor emissions. The cost of adding a precious metal costing to a trap-oxidizer would be small compared to the advantages gained. This type is discussed further in Section 7.4.

5.3 Costs and cost-effectiveness

This section presents our estimates of the costs of four of the leading candidate trap-oxidizer systems in each of the four major classes of heavy-duty diesel vehicles: light-heavy, medium-heavy, heavy-heavy, and transit bus. Cost estimates are developed for the following four systems.

1. A catalyst-coated ceramic monolith trap using an electric heater and exhaust bypass for regeneration. This type of system (sometimes without the catalyst coating) is presently considered the leading candidate system by more manufacturers than any other.

2. A catalyst-coated ceramic monolith trap using a diesel fuel burner and exhaust bypass for regeneration.

3. A catalyst-coated ceramic monolith trap regenerated by increasing the exhaust temperature. Exhaust temperature is increased by bypassing the intercooler, retarding injection timing, reducing the airflow with a variable geometry turbocharger, and/or closing a restriction valve in the exhaust. A prototype system of this type has been successfully tested by at least one U.S. manufacturer.

4. The system currently deployed by Daimler-Benz, consisting of a ceramic fiber coil trap regenerated by injecting catalytic material into the exhaust stream.

Tables 5-1 through 5-4 display the estimated initial and life-cycle costs for each type of system installed in each class of heavy-duty vehicle. The cost-estimating procedure and assumptions used in developing these estimates were taken directly from the 1984 ERC report (Weaver et al., 1984). The basic procedure is an adaptation of the method developed by Fronk (1984), based on earlier work by Lindgren (1977). Key assumptions made in developing these estimates include--in addition to the assumptions shown in the tables--a real interest/discount rate of 10 percent per year, and uniform annual mileage over the life of the vehicle. The latter is an oversimplification, of course, but the error so introduced is small.

The reader is cautioned that all of the cost estimates shown in Tables 5-1 through 5-4 are only rough approximations, and they are heavily dependent on the specific assumptions made. Estimates of trap-oxidizer system cost prepared by engine manufacturers are typically much higher than these values, while estimates prepared by EPA (1984) were significantly lower. We believe that the values shown are reasonable, and perhaps somewhat conservative, but no data exist to confirm or falsify them.

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TABLE 5-1. ESTIMATED INITIAL AND LIFE-CYCLE COSTS FOR A MONOLITH/BYPASS ELECTRIC HEATER TRAP-OXIDIZER SYSTEM

	LIGHT-HEAVY	MEDIUM-HEAVY	HEAVY-HEAVY	TRANSIT BUS
HARDWARE COST TO MANUFACTURER				
Trap	$72	$120	$240	$150
Catalyst Coating	50	70	140	80
Container and Piping	50	60	120	60
Heater and Controls	110	120	140	120
Modifications to Vehicle	15	30	60	75
TOTAL HARDWARE COST	$297	$400	$700	$485
Assembly Labor (Hours)	1.0	1.5	3.0	2.0
Cost @$24/hr	$24	$36	$72	$48
Assembly Overhead @40%	10	14	29	19
TOTAL COST TO MANUFACTURER	$331	$450	$801	$552
Manufacturer's Markup @20%	$66	$90	$160	$110
Estimated Tooling Cost Per Unit	3	30	30	60
Estimated R&D Cost Per Unit	15	150	150	300
INCREASE IN DEALER COST	$415	$720	$1,141	$1,023
Dealer's Markup @8%	$33	$58	$91	$82
INITIAL COST TO CONSUMER	$448	$778	$1,232	$1,104
OPERATING COSTS				
Vehicle Lifetime (miles)	120,000	300,000	700,000	480,000
Vehicle Lifetime (years)	8	10	10	12
Maintenance Costs				
Per 100,000 miles	$40	$40	$50	$40
Discounted Lifetime	$32	$74	$215	$109
Fuel Consumption				
Base Fuel Economy (MPG)	16.4	8.2	6.7	4.7
Reduction Due To Trap	4.0%	4.0%	3.2%	4.5%
Cost of Fuel ($/Gallon)	$0.70	$0.70	$0.70	$0.70
Discounted Lifetime Cost	$137	$631	$1,434	$1,834
Trap Replacement Cost				
Trap Lifetime (Miles)	150,000	200,000	250,000	200,000
Trap Replacements Needed	0	1	2	2
Cost of Replacement	$434	$590	$1,090	$670
Discounted Replacement Cost	$0	$313	$1,327	$674
TOTAL OPERATING COSTS	$169	$1,017	$2,976	$2,618
TOTAL LIFECYCLE COSTS	$617	$1,795	$4,208	$3,722
EQUIVALENT ANNUAL COST	$116	$292	$685	$546

TABLE 5-2. ESTIMATED INITIAL AND LIFE-CYCLE COSTS FOR A MONOLITH/BYPASS BURNER TRAP-OXIDIZER SYSTEM

	LIGHT-HEAVY	MEDIUM-HEAVY	HEAVY-HEAVY	TRANSIT BUS
HARDWARE COST TO MANUFACTURER				
Trap	$72	$120	$240	$150
Catalyst Coating	50	70	140	80
Container and Piping	50	60	120	60
Burner and Controls	170	180	220	180
Modifications to Vehicle	20	40	80	100
TOTAL HARDWARE COST	$362	$470	$800	$570
Assembly Labor (Hours)	2.0	3.0	5.0	4.0
Cost @$24/hr	$48	$72	$120	$96
Assembly Overhead @40%	19	29	48	38
TOTAL COST TO MANUFACTURER	$429	$571	$968	$704
Manufacturer's Markup @20%	$86	$114	$194	$141
Estimated Tooling Cost Per Unit	5	50	50	100
Estimated R&D Cost Per Unit	15	150	150	300
INCREASE IN DEALER COST	$535	$885	$1,362	$1,245
Dealer's Markup @8%	$43	$71	$109	$100
INITIAL COST TO CONSUMER	$578	$956	$1,471	$1,345
OPERATING COSTS				
Vehicle Lifetime (miles)	120,000	300,000	700,000	480,000
Vehicle Lifetime (years)	8	10	10	12
Maintenance Costs				
Per 100,000 miles	$120	$120	$180	$240
Discounted Lifetime	$96	$221	$774	$654
Fuel Consumption				
Base Fuel Economy (MPG)	16.4	8.2	6.7	4.7
Reduction Due To Trap	3.0%	3.0%	2.5%	4.0%
Cost of Fuel ($/Gallon)	$0.70	$0.70	$0.70	$0.70
Discounted Lifetime Cost	$103	$473	$1,120	$1,631
Trap Replacement Cost				
Trap Lifetime (Miles)	150,000	200,000	250,000	200,000
Trap Replacements Needed	0	1	2	2
Cost of Replacement	$434	$590	$1,090	$670
Discounted Replacement Cost	$0	$313	$1,327	$674
TOTAL OPERATING COSTS	$199	$1,007	$3,222	$2,959
TOTAL LIFECYCLE COSTS	$777	$1,963	$4,692	$4,304
EQUIVALENT ANNUAL COST	$146	$319	$764	$632

TABLE 5-3. ESTIMATED INITIAL AND LIFE-CYCLE COSTS FOR A MONOLITH/EXHAUST TEMPERATURE TRAP-OXIDIZER SYSTEM

	LIGHT-HEAVY	MEDIUM-HEAVY	HEAVY-HEAVY	TRANSIT BUS
HARDWARE COST TO MANUFACTURER				
Trap	$72	$120	$240	$150
Catalyst Coating	50	70	140	80
Container and Piping	50	60	120	60
Actuators and Controls	60	70	90	70
Modifications to Vehicle	10	20	40	50
TOTAL HARDWARE COST	$242	$340	$630	$410
Assembly Labor (Hours)	1.0	1.5	3.0	2.0
Cost @$24/hr	$24	$36	$72	$48
Assembly Overhead @40%	10	14	29	19
TOTAL COST TO MANUFACTURER	$276	$390	$731	$477
Manufacturer's Markup @20%	$55	$78	$146	$95
Estimated Tooling Cost Per Unit	$5	$50	$50	$100
Estimated R&D Cost Per Unit	$15	$150	$150	$300
INCREASE IN DEALER COST	$351	$668	$1,077	$973
Dealer's Markup @8%	$28	$53	$86	$78
INITIAL COST TO CONSUMER	$379	$722	$1,163	$1,050
OPERATING COSTS				
Vehicle Lifetime (miles)	120,000	300,000	700,000	480,000
Vehicle Lifetime (years)	8	10	10	12
Maintenance Costs				
Per 100,000 miles	$20	$30	$50	$50
Discounted Lifetime	$16	$55	$215	$136
Fuel Consumption				
Base Fuel Economy (MPG)	16.4	8.2	6.7	4.7
Reduction Due To Trap	1.5%	1.5%	1.2%	2.0%
Cost of Fuel ($/Gallon)	$0.70	$0.70	$0.70	$0.70
Discounted Lifetime Cost	$51	$237	$538	$815
Trap Replacement Cost				
Trap Lifetime (Miles)	150,000	200,000	250,000	200,000
Trap Replacements Needed	0	1	2	2
Cost of Replacement	$434	$590	$1,090	$670
Discounted Replacement Cost	$0	$313	$1,327	$674
TOTAL OPERATING COSTS	$67	$604	$2,080	$1,626
TOTAL LIFECYCLE COSTS	$446	$1,326	$3,243	$2,676
EQUIVALENT ANNUAL COST	$84	$216	$528	$393

TABLE 5-4. ESTIMATED INITIAL AND LIFE-CYCLE COSTS FOR A CERAMIC FIBER COIL TRAP/ADDITIVE INJECTION TRAP-OXIDIZER SYSTEM

	LIGHT-HEAVY	MEDIUM-HEAVY	HEAVY-HEAVY	TRANSIT BUS
HARDWARE COST TO MANUFACTURER				
Trap	$120	$150	$300	$200
Container and Piping	50	60	120	60
Injection and Control System	140	160	200	160
Modifications to Vehicle	20	40	80	100
TOTAL HARDWARE COST	$330	$410	$700	$520
Assembly Labor (Hours)	2.0	3.0	5.0	4.0
Cost @$24/hr	$48	$72	$120	$96
Assembly Overhead @40%	19	29	48	38
TOTAL COST TO MANUFACTURER	$397	$511	$868	$654
Manufacturer's Markup @20%	$79	$102	$174	$131
Estimated Tooling Cost Per Unit	5	50	50	100
Estimated R&D Cost Per Unit	15	150	150	300
INCREASE IN DEALER COST	$497	$813	$1,242	$1,185
Dealer's Markup @8%	$40	$65	$99	$95
INITIAL COST TO CONSUMER	$536	$878	$1,341	$1,280
OPERATING COSTS				
Vehicle Lifetime (miles)	120,000	300,000	700,000	480,000
Vehicle Lifetime (years)	8	10	10	12
Maintenance Costs				
Per 100,000 miles	$80	$80	$120	$200
Discounted Lifetime	$64	$147	$516	$545
Fuel Consumption				
Base Fuel Economy (MPG)	16.4	8.2	6.7	4.7
Reduction Due To Trap	1.0%	1.0%	0.8%	1.3%
Cost of Fuel ($/Gallon)	$0.70	$0.70	$0.70	$0.70
Discounted Lifetime Cost	$34	$158	$336	$510
Trap Replacement Cost				
Trap Lifetime (Miles)	100,000	150,000	200,000	100,000
Trap Replacements Needed	1	2	3	4
Cost of Replacement	$430	$510	$930	$610
Discounted Replacement Cost	$228	$513	$1,659	$1,393
TOTAL OPERATING COSTS	$326	$819	$2,511	$2,448
TOTAL LIFECYCLE COSTS	$862	$1,697	$3,852	$3,728
EQUIVALENT ANNUAL COST	$162	$276	$627	$547

6.0 NON-TRAP AFTERTREATMENT TECHNOLOGIES

In addition to trap-oxidizer systems, a number of other aftertreatment emissions control systems are under development for heavy-duty diesel engines. One very promising approach is the use of a flow-through catalytic converter to reduce PM and HC emissions. Research on electrostatic and electrostatic/inertial systems for particulate collection is also continuing. Finally, a number of aftertreatment technologies for NO_x reduction are also available or under development, although none are considered practical for vehicular applications.

6.1 Catalytic converters

Recent dramatic progress in in-cylinder particulate control has greatly reduced engine-out particulate levels. This progress has been most effective in reducing the solid soot fraction of the particulate, so that soluble organic fraction (SOF) of the particulate matter now accounts for a larger share than previously. Depending on the engine and operating conditions, the SOF may account for from 30 to more than 70 percent of the engine-out particulate.

Like a catalytic trap, a diesel catalytic converter would oxidize a large part of the hydrocarbon constituents of the SOF, as well as gaseous HC, CO, odor, and mutagen emissions. Unlike a catalytic trap however, a flow-through catalytic converter would not collect any of the solid particulate matter, which would simply pass in the exhaust. This would eliminate the need for a regeneration system (with its attendant technical difficulties and costs). The particulate control efficiency of the catalytic converter would, of course, be much less than that of a trap. However, a particulate control efficiency of even 25 to 35 percent would be enough to bring many current development engines (which are emitting in the 0.25 to 0.28 g/BHP-hr range without aftertreatment) within the target range for the 1991 standard.

Diesel catalytic converters would have a number of advantages. In addition to reducing particulate emissions enough to comply with the 1991 standard, the oxidation catalyst would greatly reduce HC, CO, and odor, emissions. The catalyst is also very efficient in reducing gaseous and particle-bound toxic air contaminants such as aldehydes, polynuclear aromatics, and nitroaromatics. While a precious-metal catalyzed particulate trap would have the same advantages, the catalytic converter would be much less complex, bulky, and expensive. The estimated initial, life-cycle, and equivalent annual costs of a diesel catalytic converter system in each class of heavy-duty diesel vehicle are shown in Table 6-1. Unlike the trap, the catalytic converter would have little impact on fuel economy or safety, and would probably not require periodic replacement. There would thus be little incentive for tampering with a catalytic converter.

Unlike the trap-oxidizers, the catalytic converter is a relatively mature technology--millions of catalytic converters are in use on gasoline vehicles, and Englehard Corporation PTX (tm) diesel catalytic converters have been used in underground mining applications for more than 20 years.

The primary disadvantage of the diesel catalytic converter is its relatively low collection efficiency, which would make it impossible to meet the 1994 particulate standard. This system would thus be limited to the 1991-1993 model years, if the 0.1 g/BHP-hr standard for 1994 is retained. The other disadvantages of the catalytic converter are the same as those of the precious-metal catalyzed particulate trap: sulfate emissions and conversion of NO to the more toxic NO_2. The NO to NO_2 conversion occurs naturally in the atmosphere, so the only differences in NO_2 exposure would occur where people are exposed to relatively fresh exhaust. The increase in the toxic effects of NO_2 under these circumstances should be more than counterbalanced by the decrease in CO, aldehydes, PAH, and nitroaromatics.

The tendency of the precious-metal catalyst to convert SO_2 to particulate sulfates would require the use of low-sulfur fuel: otherwise, the increase in sulfate emissions would more than counterbalance the decrease in SOF. Even at 0.04% sulfur in the fuel, preliminary tests by one manufacturer showed

TABLE 6-1. ESTIMATED INITIAL AND LIFE-CYCLE COSTS FOR A DIESEL CATALYTIC CONVERTER SYSTEM

	LIGHT-HEAVY	MEDIUM-HEAVY	HEAVY-HEAVY	TRANSIT BUS
HARDWARE COST TO MANUFACTURER				
Substrate	$20	$35	$ 70	$45
Catalyst Coating	50	70	140	80
Container and Piping	40	50	100	50
Modifications to Vehicle	10	20	40	50
TOTAL HARDWARE COST	**$120**	**$175**	**$350**	**$225**
Assembly Labor (Hours)	0.5	0.6	1.5	1.0
Cost @$24/hr	$12	$14	$36	$24
Assembly Overhead @40%	5	6	14	10
TOTAL COST TO MANUFACTURER	**$137**	**$195**	**$400**	**$259**
Manufacturer's Markup @20%	$27	$39	$80	$52
Estimated Tooling Cost Per Unit	3	15	15	30
Estimated R&D Cost Per Unit	5	50	50	100
INCREASE IN DEALER COST	**$172**	**$299**	**$545**	**$440**
Dealer's Markup @8%	$14	$24	$44	$35
INITIAL COST TO CONSUMER	**$186**	**$323**	**$589**	**$476**
OPERATING COSTS				
Vehicle Lifetime (miles)	120,000	300,000	700,000	480,000
Vehicle Lifetime (years)	8	10	10	12
Maintenance Costs				
Per 100,000 miles	$10	$15	$20	$20
Discounted Lifetime	$8	$28	$86	$55
Fuel Consumption				
Base Fuel Economy (MPG)	16.4	8.2	6.7	4.7
Reduction Due To Trap	0.5%	0.5%	0.5%	0.5%
Cost of Fuel ($/Gallon)	$0.70	$0.70	$0.70	$0.70
Discounted Lifetime Cost	$17	$79	$224	$204
Replacement Cost				
Lifetime (Miles)	150,000	350,000	400,000	250,000
Trap Replacements Needed	0	0	1	1
Cost of Replacement	$310	$400	$710	$440
Discounted Replacement Cost	$0	$0	$412	$243
TOTAL OPERATING COSTS	$25	$107	$722	$501
TOTAL LIFECYCLE COSTS	$211	$430	$1,311	$976
EQUIVALENT ANNUAL COST	$40	$70	$213	$143

sulfur accumulation and increasing sulfate emissions with time. As discussed in Section Five, however, precious-metal catalyst formulations with relatively low sulfate conversion tendencies have been developed for use in particulate traps. Any sulfate conversion problems at the 0.05% sulfur level could be controlled by using one of these formulations, albeit with some sacrifice in catalyst activity.

6.2 Electrostatic Agglomerator/Precipitators

Electrostatic precipitators have been used in a number of novel approaches to particulate emissions control for new engines. An electrostatic agglomerator has been used as the front end in an experimental system for removing diesel particles by cyclone collection developed by Robert Bosch AG (Polach and Hagele, 1984), and a similar system has been proposed by Kittelson and coworkers (1986). Another system proposed by Yang (1981) used an electrostatic precipitator for collection, followed by particle destruction by means of an electrostatic discharge.

The Bosch researchers developed a fairly compact agglomerator system using serrated "spray disks" to increase the corona discharge and charging rate of the particles. This system was developed as a "pre-agglomerator" for a cyclone collection system, as shown in Figure 6-1. The system initially included a separate electrostatic collector section like an electrostatic precipitator. However, this section was subsequently found to be unnecessary for agglomeration purposes--corona discharge alone sufficed to give better than 90 percent collection in the cyclones in steady-state testing.

A prototype of the Bosch system was tested on a light-duty vehicle using the U.S. Federal Test Procedure. The particulate mass collection efficiency on this test was measured at 58 percent, which is significantly lower than the steady-state results measured, but still quite impressive. In the light-duty vehicle tests, the Bosch system was reported to give the same muffling capability as a muffler, while occupying the space required by 1 1/2

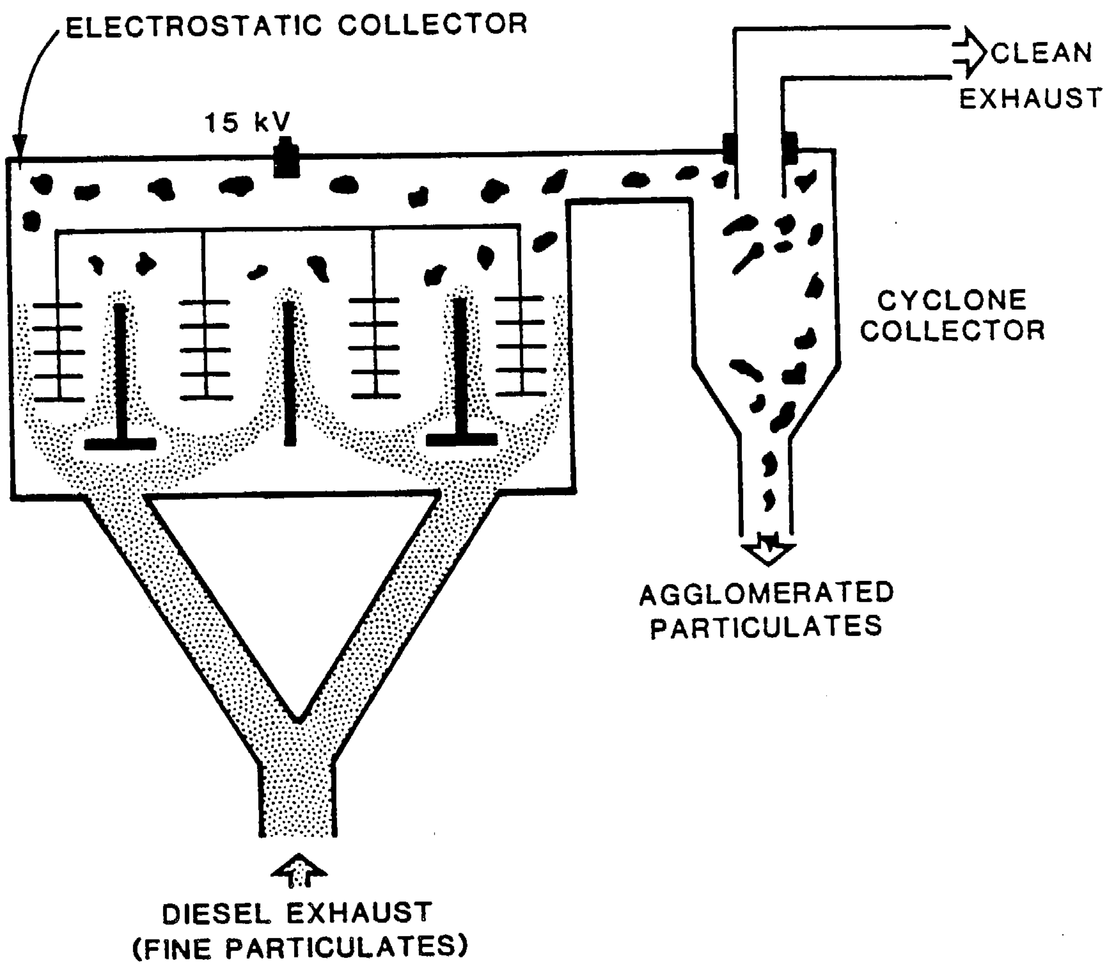

Figure 6-1. Schematic Diagram of the Combined Electrostatic Collector-Cyclone Separation Device.

Source: Polach and Hagele, 1984.

mufflers. It was also indicated that the system resulted in a 3 percent increase in fuel consumption, which was stated as being primarily due to the electric power requirements of the agglomerator. Some increase in fuel consumption from increased backpressure in the cyclones would also be expected.

A similar system has been proposed by Kittelson and coworkers (1986). In this approach, particles are collected and agglomerated by a multiplate electrostatic precipitator. Kittelson et al. discovered that diesel particles have a significant charge as they leave the engine, therefore, no separate charging system is needed. After sufficient particulate matter has built up on the plates, the agglomerated particles begin to be re-intrained by the exhaust gas. They can then be collected downstream by a cyclone or other inertial filter.

The key problem with both the Bosch system and the approach of Kittelson et al. lies in disposing of the collected particulate matter. In the Bosch system, a high-particulate gas stream is recycled into the engine and burned. This would be infeasible in a turbocharged engine, due to the potential fouling of the compressor and intercooler with particulate matter. All of the engine manufacturer's reservations about EGR systems would also apply to this system as well. Unless this problem can be resolved, the electrostatic collection approach to particulate control is unlikely to proceed beyond the laboratory.

6.3 NOx Reduction Techniques

The process of catalytic NO_x reduction used on light-duty gasoline vehicles is inapplicable to diesels. Because of their heterogeneous combustion process, diesel engines require substantial excess air, and their exhaust thus inherently contains significant excess oxygen. The three-way catalysts used on automobiles require a precise stoichiometric mixture in the exhaust in order to function--in the presence of excess oxygen, their NO_x conversion effiency rapidly approaches zero.

A number of aftertreatment NO_x reduction techniques which will work in an oxidizing exhaust stream are currently available or under development for stationary pollution sources. These include selective catalytic reduction (SCR), selective non-catalytic reduction (Thermal Denox(tm)), and reaction with cyanuric acid (RapReNox(tm)). However, each of these systems requires a continuous supply of some reducing agent such as ammonia or cyanuric acid to react with the NO_x. Because of need for frequent replenishment of this agent, and the difficulty of ensuring that the replenishment is performed when needed, such systems are considered impractical for vehicular use. Even if the replenishment problems could be resolved, these systems would raise serious questions about crash safety and possible emissions of toxic air contaminants. They will not be considered further in this report, therefore.

7.0 REGULATORY ISSUES WITH THE CURRENT EMISSIONS STANDARDS

In the course of research on this project, a number of significant questions and issues concerning the present heavy-duty diesel emissions regulations became apparent. These questions include the following.

1. Current variability in particulate emissions measurements, and the implications for determining compliance with very low emissions standards.

2. Diesel fuel sulfur and aromatic hydrocarbon content, and the implications for aftertreatment controls.

3. Cost-effectiveness of meeting the 1994 particulate standard, given that compliance with the 1991 standard appears feasible without trap-oxidizers.

4. Desirability of a precious-metal catalyst requirement for heavy-duty diesel vehicles.

A detailed investigation of these issues is beyond the scope of the present work, but their importance is such that we considered it necessary to raise them at this time. We recommend that ARB staff consider each of the questions, and possibly undertake additional investigative work to resolve them.

7.1 Measurement Variability

The range of test-to-test and laboratory-to-laboratory variations in diesel PM and HC measurements is fairly large. The confidence interval (based on +/- two standard deviations) for PM measurements in EPA's 1982 round-robin study was 0.04 g/BHP-hr for measurements made in the same laboratory, while the lab-to-lab confidence interval was 0.20 g/BHP-hr. A repeat study in 1986 gave confidence intervals of 0.08 g/BHP-hr within the same laboratory, and 0.17 g/BHP-hr lab-to-lab (Navistar, 1987).

These variability data were derived from measurements on engines with base emissions levels of about 0.6 g/BHP-hr particulate. The absolute level of variability in the emissions measurements would be expected to be somewhat lower at the lower emissions levels required by the 1991 and 1994 standards, however. The available data suggest that this reduction in variability is <u>not</u> proportional to the reduction in the underlying emissions measurement, however, so that the fractional variability in the measurements becomes larger as the measurements themselves become smaller.

So much variability in the emissions measurements would make it difficult for a manufacturer to be certain of passing a Selective Enforcement Audit even at the 0.25 g/BHP-hr level, and would make it virtually impossible to assess compliance with the 0.1 g/BHP-hr standard. It appears that further development and refinement of the particulate emissions measurement methods may be required in order to reliably determine compliance with such low emissions standards.

7.2 Diesel Fuel Sulfur and Aromatic Content

The effects of diesel fuel sulfur and aromatic hydrocarbon content on emissions were addressed in a previous report by one of the authors and others (Weaver et al., 1985). Based on the limited data then available, this report concluded that reducing the fuel aromatic content would significantly reduce diesel NO_x, HC, and PM emissions; while reducing the sulfur content would reduce PM emissions and corrosive wear, thus increasing engine life. The savings due to extended engine life were projected to more than compensate for the increased refining cost to remove the sulfur, resulting in a net <u>economic</u> benefit to society, as well as substantial environmental benefits. These conclusions proved highly controversial.

Since the publication of the 1985 report, considerable new data has come to light on the relationship between fuel sulfur and engine wear. In submissions to EPA, virtually every heavy-duty engine manufacturer has stated that reducing fuel sulfur will beneficially affect engine life (although many stated that the benefits estimated by Weaver et al. were overestimated). However, preliminary results from a study of oil analyses in Southern California RTD buses show roughly a 30 percent reduction in wear metals in switching from the previous fuel to fuel containing 0.05 percent sulfur. Tests by a major engine manufacturer in a low-emission engine with air to air intercooling showed more than a two-thirds reduction in piston ring wear rate in going from 0.27 percent to 0.05 percent sulfur in the fuel. Low-emission engines would be expected to be more susceptible to corrosive wear, since their low exhaust temperatures and high boost pressures would make it easier for sulfuric acid to condense on the cylinder walls.

Fuel sulfur may also be a major reason for the increase in diesel engine wear due to EGR, as discussed in Section 4.4. If so, low sulfur fuel would be required in order for EGR to become a practical emission control technique for heavy-duty diesel engines.

Reducing the sulfur level in diesel fuel would have a direct and immediate impact on diesel particulate emissions. Measurements of the effect of going from 0.3 percent sulfur to 0.05 percent show a reduction in particulate emissions of 0.05 to 0.10 g/BHP-hr, with a typical reduction of about 0.07 g/BHP-hr. This is more than 25 percent of the 1991 standard, and 70 percent of the 1994 standard. For this reason, nearly all of the engine manufacturers contacted in this study strongly urged the adoption of a low-sulfur requirement for diesel fuel (with corresponding changes in certification fuel) by 1991. Failing this, they urged the adoption of 0.05 percent sulfur for <u>certification</u> fuel in 1991, with a sulfur limit for commercial diesel fuel to follow as soon as practicable. All manufacturers felt that such a limit would greatly assist them in meeting the 1991 standard without traps, and most stated that it would probably be impossible to do so without it.

Reducing the sulfur level in diesel fuel will also be essential before any widespread deployment of precious metal catalysts (whether in catalytic traps or diesel catalytic converters) could be possible. As discussed in Section Six, catalytic converters could be a very attractive alternative to traps for compliance with the 1991 particulate standard. In addition, as discussed in Section 7.4 below, the use of such catalysts would be very desirable for the control of gaseous hydrocarbons, toxic air contaminants, and odor emissions from diesel vehicles.

Reducing the aromatic hydrocarbon content of diesel fuel would also help to reduce PAH and nitro-PAH emissions as well as HC, NO_x, and PM emissions from new and existing diesels.

The maximum benefits of reducing fuel sulfur content will not be attained unless the diesel engine manufacturers are able to plan on its reduction. In California, at least, the major controversy over diesel fuel regulation appears to be not whether to implement a sulfur limit, but whether an aromatic hydrocarbon limit should be imposed at the same time. If this is in fact the case, diesel engine manufacturers would benefit considerably from a firm policy statement by ARB, to the effect that <u>either</u> a low-sulfur or a low-sulfur/low-aromatic fuel specification will be imposed, and that low-sulfur fuel may be used for certification in 1991.

7.3 <u>Cost-Effectiveness of the 1994 Particulate Standard For Trucks</u>

When the 1991 and 1994 particulate standards were originally set, it was assumed that trap-oxidizers would be required on most vehicles in order to comply with the the 1991 standard. The additional cost of increasing trap-oxidizer efficiency to comply with the 1994 standard was therefore assumed to be small. It now appears, however that most heavy-duty diesel engines will <u>not</u> require trap oxidizers in order to meet the 0.25 g/BHP-hr in 1991, but that all engines <u>would</u> require traps to meet the 1994 standard. Under these circumstances, it is reasonable to question whether the 1994 particulate limit is still cost-effective.

The actual emissions reduction resulting from any particular emissions regulation, and thus its cost-effectiveness, cannot be calculated from a comparison of emissions standards alone. Instead, it should be calculated from an estimate of the change in-use emissions that would result from the adoption of the standard. In recent work for ARB, Radian estimated the in-use emission factors for different classes of heavy-duty diesel trucks of different model years under a variety of assumed I/M scenarios (Weaver and Klausmeier, 1987a). By comparing the in-use emission factors estimated for the 1993 model year vehicles (which were assumed to comply with the 0.25 g/BHP-hr standard) and the 1994 vehicles (assumed to comply with the 0.10 g/BHP-hr standard), it is possible to estimate the reduction in in-use emissions due to the 1994 standard.

Table 7-1 shows our rough calculations of the emissions per vehicle under each of the two emissions standards, as well as the incremental cost-effectiveness of the 1994 particulate limit. Calculations were performed for three different sets of in-use deterioration factors. The first set assumes no deterioration: i.e. all vehicles perform like certification vehicles. The second set employs our estimated deterioration factors for the case where no heavy-duty diesel I/M program is in place. As might be expected, total emissions under this scenario are much higher. The third set employs our estimated deterioration factors under our most effective I/M scenario. Emissions in this case are substantially lower than in the no I/M case, but still much higher than the no-deterioration scenario.

The annual costs of meeting the 1994 standard were taken as equal to the annual cost per vehicle for the lowest cost trap-oxidizer system (from Table 5-3). However, some heavy-duty vehicles would require trap-oxidizers or catalytic converters to comply even with the 1991 standards. In developing the emissions factors in Weaver and Klausmeier (1987a), we assumed that 10 percent of heavy-heavy trucks, 30 percent of medium-heavy trucks, and 50 percent of

TABLE 7-1. COST-EFFECTIVENESS OF THE 1994 PARTICULATE STANDARD

	LIGHT-HEAVY	MEDIUM-HEAVY	HEAVY-HEAVY
COSTS PER VEHICLE			
Percent with Cat. Converter			
at 0.25 g/BHP-hr	50%	50%	40%
at 0.10 g/BHP-hr	0%	0%	0%
Percent with Trap-Oxidizer			
at 0.25 g/BHP-hr	50%	30%	10%
at 0.10 g/BHP-hr	100%	100%	100%
Annual Cost			
Cat. Converter	$40	$70	$213
Trap-Oxidizer	$84	$216	$528
NET CHANGE IN AVG. COST/VEHICLE	$22	$116	$390
EMISSION REDUCTIONS PER VEHICLE			
Emission Factor (g/mile)			
No deterioration			
at 0.25 g/BHP-hr	0.21	0.48	0.68
at 0.10 g/BHP-hr	0.07	0.17	0.25
With Deterioration--No I/M			
at 0.25 g/BHP-hr	0.81	1.68	2.10
at 0.10 g/BHP-hr	0.62	1.43	1.57
With Deterioration--Best I/M			
at 0.25 g/BHP-hr	0.44	1.00	1.44
at 0.10 g/BHP-hr	0.25	0.57	0.77
Avg. Annual mileage	15,000	30,000	70,000
Total Emissions (lb/vehicle-year)			
No deterioration			
at 0.25 g/BHP-hr	6.9	31.7	104.8
at 0.10 g/BHP-hr	2.3	11.2	38.5
With Deterioration--No I/M			
at 0.25 g/BHP-hr	26.8	111.0	323.8
at 0.10 g/BHP-hr	20.5	94.5	242.1
With Deterioration--Best I/M			
at 0.25 g/BHP-hr	14.5	66.1	222.0
at 0.10 g/BHP-hr	8.3	37.7	118.7
COST-EFFECTIVENESS OF 1994 STANDARD ($/TON PM)			
No deterioration	$9,607	$11,349	$11,760
With Deterioration--No I/M	$7,079	$14,073	$9,541
With Deterioration--Best I/M	$7,079	$8,182	$7,548

light-heavy trucks would require trap-oxidizers at 0.25 g/BHP-hr. Another 40 percent of heavy-heavy trucks, 50 percent of medium-heavy trucks, and 50 percent of light-heavy trucks were assumed to require catalytic converters. Subtracting the credit for trap-oxidizers that were already in place and catalytic converters that were no longer needed, gave the net change in average cost per vehicle shown in Table 7-1.

The cost-effectiveness values calculated under each scenario are shown at the bottom of Table 7-1. The costs per ton of diesel particulate removed in the no deterioration case range from $9,600 to about $11,800 per ton. This is toward the high end of the cost-effectiveness range for existing particulate control measures. Surprisingly, the cost-effectiveness for two of the truck classes is <u>better</u> under the no I/M scenario than the no-deterioration scenario. Widespread tampering and disablement of trap-oxidizers were projected under this scenario, and this was expected to increase the costs per ton substantially. This effect was offset, however, by the fact that those traps which were <u>not</u> tampered with would intercept a large part of the excess PM emissions resulting from other types of defects, resulting in a greater net emissions reduction than for the no-deterioration case.

The best I/M program was projected to greatly reduce the incidence of tampering with traps, while having a lesser effect on other sources of excess emissions. Thus, the net emissions reduction due to the traps in this case is even greater than in the no I/M case, and the cost-effectiveness is proportionately better.

Based on these rough calculations, it appears that the cost-effectiveness of the 1994 particulate standard may be reasonably comparable to that of other PM control measures that have been undertaken. Both the PM reduction and the cost-effectiveness of the standard would be improved by a vigorous I/M program. The reader is cautioned, however, that these numbers are based on numerous unprovable assumptions, and that a change in any of the key assumptions could dramatically change the results. As an extreme example, if all engines were able to comply with the 0.25 g/BHP-hr standard without needing either traps <u>or</u> catalytic converters, the calculated cost per ton of particulate control for light-heavy duty vehicles would quadruple. For medium heavy vehicles, the cost would nearly double, while for heavy-heavy vehicles it would increase about 35 percent. We recommend that the cost-effectiveness of the 1994 standard be considered once again in about 1990, when more data on emission technology for the 1991 standard will be available.

7.4 Catalyst Desirability

As noted in Sections Five and Six, catalytic trap-oxidizers and/or catalytic converters on diesel vehicles can markedly reduce emissions of particulate SOF, as well as toxic air contaminants such as PAH, nitro-PAH, aldehydes, and aldehydes. They are also effective in reducing gaseous HC, CO, and odor emissions. While diesel HC and CO emissions are much lower than those from gasoline engines, it would be desirable to reduce them still further. Many people consider diesel odor a significant nuisance, and it undoubtedly reduces the quality of life in urban areas. Reducing SOF and particle-borne toxic air contaminants were major reasons for adopting particulate mass emissions regulations in the first place.

Based on the discussion in Section Six, it appears that a diesel catalytic converter may be a relatively cost alternative to a trap-oxidizer, for particulate standards in the 0.20 to 0.25 g/BHP-hr range. Such a system would likely result in a greater reduction in particulate SOF and carcinogen emissions than would a non-catalyzed trap-oxidizer. For lower particulate emissions levels, a trap-oxidizer is required. Adding a precious metal catalyst coating to a trap would then be relatively inexpensive, and would markedly reduce SOF and carcinogen emissions, as well as gaseous HC, CO, and odor. Either of these approaches would require the use of low sulfur fuel, in order to minimize particulate sulfate formation. Low-sulfur fuel will be required to meet the 1994 particulate standard in any case, however.

ARB should consider, therefore, the possibility of adopting an oxidation catalyst requirement for diesels, either instead of or in addition to the 1994 particulate standard. One way of doing this would be to establish HC and/or CO emissions standards for diesels at a much lower level than for gasoline engines. Another approach would be to regulate PAH and/or SOF emissions directly, but these would introduce significant measurement difficulties. A detailed analysis of the cost and cost-effectiveness of any of these requirements is beyond the scope of this report. It is recommended that such an analysis be conducted, however.

8.0 FEASIBILITY OF LOWER NO_x STANDARDS

One purpose of the research under this task was to evaluate the feasibility of a NO_x emissions standard lower than the 1991 level of 5.0 g/BHP-hr, while continuing to comply with the 1994 PM standard of 0.1 g/BHP-hr. Further NO_x reductions are limited by the tradeoff between NO_x and PM emissions, and by a similar tradeoff between NO_x and fuel economy. As injection timing is retarded further and further to reduce NO_x, fuel consumption and PM emissions increase. Eventually, an incipient misfire condition occurs, resulting in a very rapid increase in fuel consumption, HC, and PM. With current technology engines, point of rapid PM and HC increase occurs at a NO_x level of about 3.5 to 4 g/BHP-hr.

Figure 8-1, taken from an earlier report by one of the authors, shows the relationship between NO_x emissions and fuel economy for a number of heavy-duty diesel engines. This relationship is shown for engines with both conventional and electronically optimized fuel injection timing. As this figure shows, electronic controls are able to minimize the adverse effects of retarded timing down to about 5.0 g/BHP-hr NO_x. Further NO_x reductions result in a very rapid fuel consumption increase.

Figure 8-2, taken from the paper by Cartellieri and Wachter (1987) shows the NO_x/PM tradeoff for a number of variations on AVL's ultra-low emissions development engine. Again, the rapid increase in emissions is apparent below about 4.4 g/BHP-hr NO_x. Since the AVL engine represents the current state of the art in diesel emissions control, it can be stated that current emission control technology does not permit a NO_x standard below about 4.5 g/BHP-hr without serious degradation of PM emissions and fuel economy.

The increase in PM emissions due to a lower NO_x standard can be controlled to some degree by the use of a trap-oxidizer. Since it now appears that trap-oxidizers will be required to meet the 1994 PM standard in any case, it has been argued that a lower NO_x standard could be accommodated at little cost by a simple increase in trap-oxidizer efficiency. This would be possible

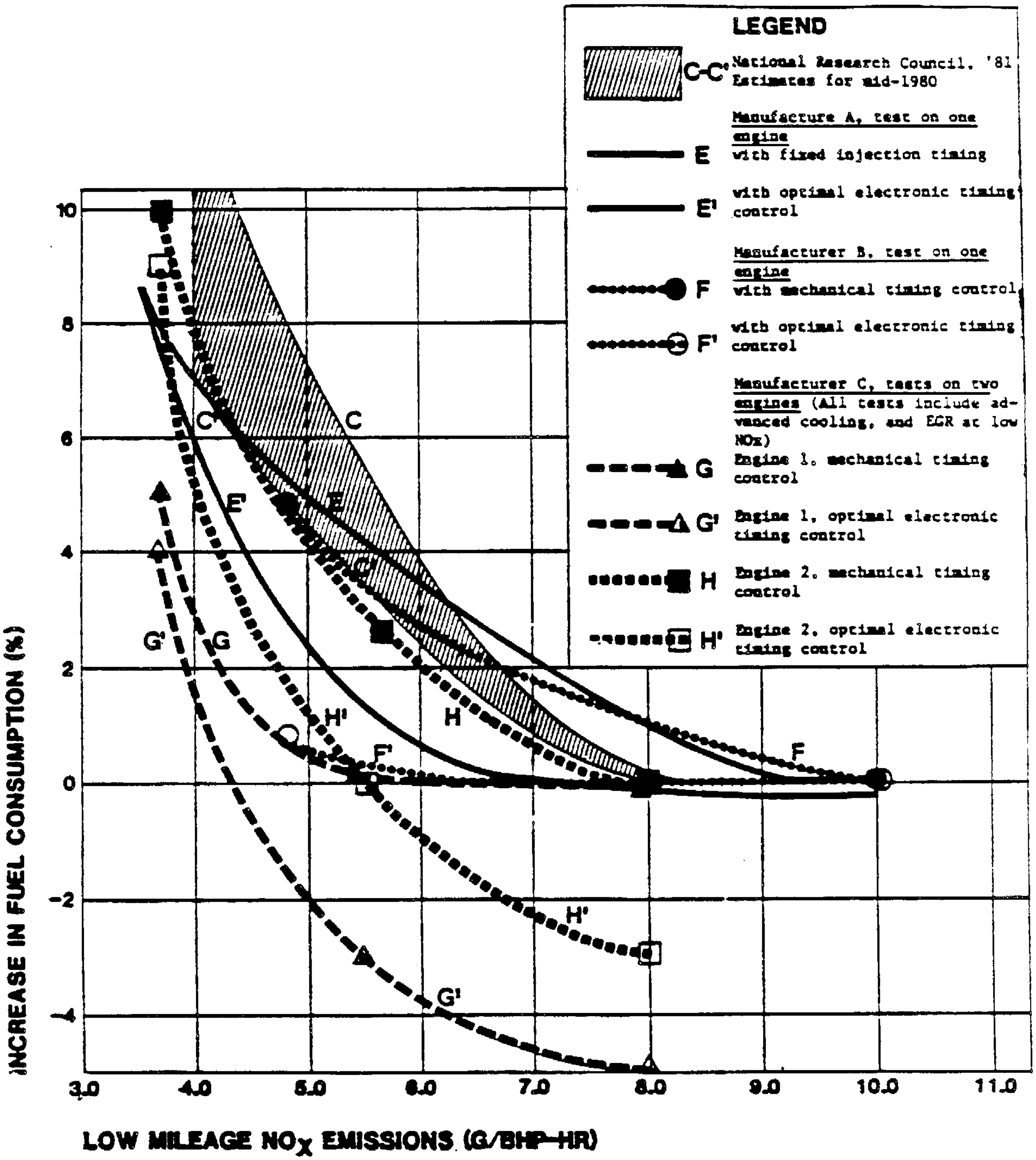

Figure 8-1. Fuel economy vs. NO emissions -- effects of electronic controls (Source: Weaver, 1984)

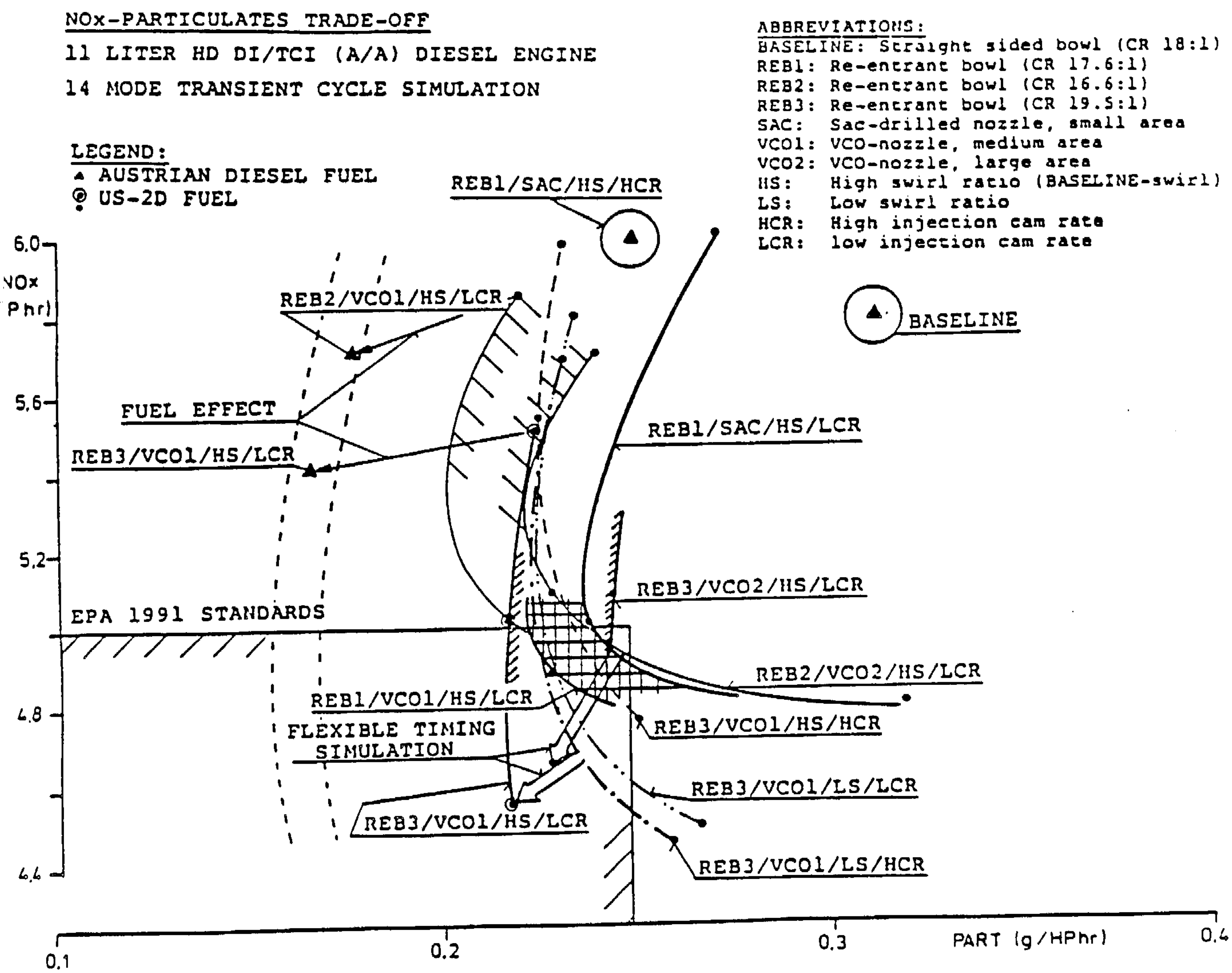

Figure 8-2. NO_x/PM Tradeoff for the AVL development engine (Source: Cartellieri and Wachter, 1987)

only to only a very limited extent, however. At the very low engine-out PM levels of current development engines, most of the particulate matter emitted consists of heavy hydrocarbons and sulfates. Existing traps are comparatively ineffective in collecting these materials, so that the trap's efficiency (measured as PM out over PM in) is reduced. Thus, manufacturers may be hard pressed to meet a 0.10 g/BHP-hr standard using traps, even with PM emissions in the 0.2 to 0.3 g/BHP-hr range. Any marked increase in PM emissions would make it nearly impossible to meet the 0.10 g/BHP-hr PM standard.

Advanced technology--Two emissions control technologies show substantial promise for improving the NO_x/PM and NO_x/fuel economy tradeoffs, thus making a much lower NO_x standard feasible. The first of these is the reduced initial rate of injection (RIRI) technique discussed in Section 4.1.1. The second is exhaust gas recirculation (EGR), discussed in Section 4.1.4.

As discussed in Section 4.1.1, data from a single-cylinder research engine on the effects of RIRI showed a remarkable impact on NO_x emissions, at very little cost in fuel economy or PM emissions. If these research engine data can be successfully translated to multicylinder production engines, a NO_x standard in the 2.5 to 3.0 g/BHP-hr range would might not be out of reach. Extrapolation from such limited data is perilous, however--much more information on the RIRI technique and its effects will be needed before such a standard could be established.

The use of EGR could also have a major impact on NO_x emissions, with minimal degradation in fuel economy and PM. As discussed in Section 4.1.4, researchers at Ford were able to reduce NO_x emissions from a light-duty DI engine by more than 50 percent (to about two g/BHP-hr in light-duty test cycle) using an optimized EGR schedule, while maintaining PM emissions comparable to light-duty IDI engines without EGR. EGR would be less effective in a heavy-duty engine, due to their more heavily loaded test cycles. The available data suggest that NO_x emissions in the 3-4 g/BHP-hr range might be achievable without greatly degrading fuel economy or PM emissions, however.

The major drawback to EGR is its detrimental effect on engine durability and maintenance costs. The reasons for this effect are not well understood, however. Some data (and some manufacturers) suggest that the sulfur dioxide in the exhaust is the major culprit, while others focus on the role of recycled carbon particles. If sulfur is the major problem, its effects could be greatly reduced by the use of low-sulfur fuel--a measure which will probably be required for the 1994 PM standard in any case. If recycled carbon is the problem, its effects should be virtually eliminated by taking the recyle stream after the trap-oxidizer. Thus, EGR's effects on engine wear might be greatly alleviated by emission control measures undertaken for other reasons.

More research is needed to establish the real causes and potential cures for excessive engine wear due to EGR. Because of their strong aversion to EGR in any form, this research is unlikely to be performed (or, if performed, made available) by the major engine manufacturers. Some public funding of research in this area would be appropriate, therefore.

The available data suggest that either the RIRI technique or EGR (or possibly both together) could make it possible to achieve a NO_x emissions standard substantially lower than 5.0 g/BHP-hr without significantly degrading fuel economy or other emissions. More research and development is required in order to establish whether this potential can actually be achieved, and what specific NO_x emissions levels are achievable. We recommend that this issue be reexamined in about 1990, with a view to establishing a new NO_x standard, if warranted, for the 1994 model year.

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A Study of Excess Motor Vehicle Emissions – Causes and Control

Section II

Enforcement Alternatives for Heavy–Duty Engine Emission Standards

prepared for:

State of California Air Resources Board

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SECTION II

A STUDY OF EXCESS MOTOR VEHICLE EMISSIONS - CAUSES AND CONTROL

Enforcement Alternatives for Heavy-Duty Engine Emission Standards

prepared for:

California Air Resources Board

December 1988

prepared by:

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EXECUTIVE SUMMARY

The legal and regulatory requirements for the use of California-certified engines in heavy-duty vehicles are surrounded by a great deal of confusion. Health and Safety Code Section 43151(a) states:

> "No person who is a resident of, or who operates an established place of business within, this state shall import, deliver, purchase, rent, lease, acquire, or receive a new motor vehicle, new motor vehicle engine, or motor vehicle with a new motor vehicle engine for use, registration, or resale in this state unless such motor vehicle engine or motor vehicle has been certified pursuant to this chapter. No person shall attempt or assist in any such action." (emphasis added)

ARB's informal policy requires that any heavy-duty vehicle registered in California, or which accumulates more than 25 percent of its annual mileage in California, must use a California-certified engine. However, this policy has not been communicated effectively to the dealer community, and is not presently being enforced.

The use of California-certified engines is intended to be enforced through the vehicle registration process. Two types of registration are available for heavy-duty vehicles: "in-state" and "apportioned". In-state registration is the same as that for light-duty vehicles, except that heavy-duty vehicles do not require Smog Certificates. To register a new light or heavy-duty vehicle in-state requires a dealer certification that the vehicle meets California emissions standards. DMV does not check that these certifications are true, however.

A "used" vehicle brought from out-of-state may be registered in California if it meets Federal emissions standards. A "used" vehicle is defined as one whose odometer shows at least 7,500 miles. Since this is 7,500 miles is less than one month's mileage for a typical line-haul truck, there is significant opportunity for abuse. Both direct and indirect evidence indicates that such abuse is common. In one scheme, the truck is "sold" to an out-of-state dummy firm, which "leases" it to the buyer for a month or two while it accumulates the needed mileage. The buyer then "buys" it "used" from the dummy firm.

"Apportioned" vehicles are registered under the International Registration Plan (IRP). California, 36 other states, and the Canadian province of Alberta are signatories to this agreement. Under this program, vehicles may register or "baseplate" in any state where the owner has a place of business, while basing and operating freely in any of the signatory states. Fleets are required to keep track of the mileage accumulated in each state, and to report it at the end of the year. These data are used to determine each state's pro rata share of the registration fees.

At present, DMV maintains no control at all over the certification status of vehicles registered under the IRP. Engines for these

vehicles do not require even Federal certification. This is due to the flexibility of the IRP--non-complying vehicles refused registration in California could simply baseplate elsewhere, while continuing to base and run within the state.

Conclusions and Recommendations

In-state registration--The present policy for in-state registrations is workable, and appears to have been reasonably successful, despite the a general lack of enforcement for heavy-duty vehicles. The following changes would improve its effectiveness.

- Institute procedures for confirming that vehicles certified by the dealer as meeting California emissions standards actually do so. Approaches include checking the VIN against manufacturers data, spot physical inspections, and periodic audits.

- Change the definition of a "used" medium-heavy or heavy-heavy duty vehicle to require that it be at least two years old.

- Institute checks of certification status and emissions control functioning as part of the inspection required for used heavy-duty vehicles.

A field study is also recommended to determine whether any significant number of heavy-duty vehicles are operating with expired or improper registrations, and the effects of this operation on emissions status.

Apportioned (interstate) registration

Under present DMV policy, vehicles registered under the Interstate Registration Plan are not required to meet any emissions standards--not even Federal certification. Because of the flexibility inherent in the IRP, neither the current ARB policy nor a strict application of the current law is likely to be very effective in promoting the use of California engines in these vehicles. Either policy would tend to encourage truckers to register out-of-state, and to purchase used vehicles for use in California. This could possibly degrade air quality rather than improving it.

An alternative approach which would avoid these perverse incentives would be to require truck fleets having significant activity in California to accumulate a large fraction of their California mileage using California engines. For example, any fleet travelling more than one million miles (or 50 percent of its total miles, whichever is less) in California could be required to demonstrate that 80 percent of this mileage was accumulated with California engines. This requirement could be enforced through the existing mileage-reporting structure of the IRP. A statutory change would be required to implement this approach.

Table of Contents

1.0 INTRODUCTION

Sierra Research and its subcontractor, Radian Corporation, are investigating a number of issues relating to excess motor-vehicle emissions under contract No. A5-188-32 with the California Air Resources Board. Task One under this contract is a study of heavy-duty diesel control options. This Task includes four subtasks (A-D), of which the first three were covered in a previous report (Weaver and Klausmeier, 1987). Issues examined in that report included technology for diesel emissions control, and fuel quality. The final subtask in Task One was a study of enforcement alternatives for heavy-duty engines, aimed at increasing the fraction of trucks operating in California that are equipped with engines meeting California emissions standards. This report presents the results of that final subtask. Although addressed primarily to heavy-duty diesel vehicles, the results of this subtask are applicable to heavy-duty vehicles powered by gasoline and other fuels as well.

1.1 Background

Diesel trucks and buses emit significant quantities of oxides of nitrogen (NO_x), particulate matter (PM), and unburned hydrocarbons (HC); both in California and in the United States as a whole. In order to control these emissions nationwide, the U.S. Environmental Protection Agency (EPA) first established emissions regulations for smoke opacity from these engines in 1970. The first regulations limiting HC, CO, and NO_x emissions from heavy-duty diesel engines were established by ARB. These regulations went into effect in California on January 1, 1973. Identical standards promulgated by EPA took effect in the rest of the U.S. in 1974. Both the ARB and EPA emissions limits have been tightened several times since 1974, and regulation of PM emissions was added beginning in 1988. Table 1.1 shows the Federal and California emissions standards in effect for heavy-duty diesel engines since 1973, along with those scheduled for future years.

Since 1975, California's NO_x emissions standard has been significantly lower than that set by EPA, requiring the development and certification of separate "California-model" engines. Because of the resulting burden on industry, California and Federal emissions standards were to have been "aligned" in the 1988 model year. EPA's standards for model year 1988 originally specified 6.0 g/BHP-hr NO_x. These limits were promulgated by EPA in 1985, and adopted by ARB in April, 1986. ARB relaxed its 5.1 g/BHP-hr NO_x standard to match the Federal standard, while simultaneously adopting the Federal PM limit of 0.6 g/BHP-hr.

This alignment was frustrated by a recent Federal court decision, which resulted in a two year delay in implementing EPA's NO_x standard (the 6.0 g/BHP-hr standard for California was not affected by this decision). As a result, Federal and California emissions standards will not be fully aligned until the 1990 model year. Both sets of

TABLE 1-1. FEDERAL AND CALIFORNIA EMISSIONS REGULATIONS FOR HEAVY-DUTY DIESEL ENGINES

	CO (g/BHP-hr)	HC (g/BHP-hr)	NOx (g/BHP-hr)	PM (g/BHP-hr)	Test Procedure	Smoke Opacity (Acc/Lug/Peak,%)
Federal						
1974-1978	40		16[a]	NR	13-Mode	20/15/50
1979-1984	25	1.5	10[a]	NR	13-Mode	20/15/50
1985-1987	15.5	1.3	10.7	NR	Transient	20/15/50
1988-1989	15.5	1.3	10.7	0.6	Transient	20/15/50
1990	15.5	1.3	6.0	0.6	Transient	20/15/50
1991-1993	15.5	1.3	5.0	0.25	Transient	20/15/50
1994+	15.5	1.3	5.0	0.1	Transient	20/15/50
California						
1973-1974	40		16[a]	NR	13-Mode	b
1975-1976	30		10[a]	NR	13-Mode	b
1977-1979	25	1.0	7.5	NR	13-Mode	b
1980-1983	25	1.0	6.0[a]	NR	13-Mode	b
1984-1987	15.5	1.3	5.1	NR	Transient	b
1988-1990	15.5	1.3	6.0	0.6	Transient	b
1991-1993	15.5	1.3	5.0	0.25	Transient	b
1994+	15.5	1.3	5.0	0.1	Transient	b

NR: Not regulated
a Sum of NOx plus HC emissions
b Federal Smoke Standard applies

standards are then scheduled to undergo substantial tightening in 1991, and again in 1994.

In the past, effective enforcement of more stringent California standards has been difficult. The application of California emissions requirements to trucks operating in interstate commerce has been an area of significant confusion. As a result, few such trucks have used California-certified engines. The possible sale of new or nearly-new Federal trucks as "used" vehicles in California is also of concern.

Because of California's lower NO_x standards, California engines are often inferior in fuel economy and power output and higher in cost than similar engines calibrated to meet the Federal emissions standards. Thus, truck purchasers have had an incentive to avoid the use of California engines where possible, and it appears that many have been successful in doing so. In addition, California-based trucking firms have argued that the more stringent regulations impose additional costs on them, placing them at a competitive disadvantage with out-of-state firms.

Enforcement problems contributed to the 1986 decision to align the California heavy-duty emissions standards with the Federal ones. However, ARB retains the option to establish standards at a lower level, if this is found to be necessary and feasible. Should this happen, the question of how to enforce the use of California rather than Federal engines would again become important.

1.2 Outline of the Report

This report is divided into six sections, of which this Introduction is the first. Section Two describes the legal basis for requiring the use of California-certified engines, and present ARB policy concerning that use. Since the primary vehicle for enforcing this requirement is through the registration process, Section Three discusses present vehicle registration policies and options for heavy-duty vehicles, and their enforcement.

A key conclusion of this report is that - due to inadequate communication of the current policies - many heavy-duty truck dealers are operating under misconceptions concerning certification requirements. Section Four summarizes our discussions with dealership personnel at four local dealerships, and their current practices and understanding. Section Five contains our analysis of the situation and our recommendations and conclusions. Section Six is a bibliography of references cited.

2.0 LEGAL BASIS AND ARB POLICY

The basic statutory language regarding requirements for the sale and use of California certified heavy-duty engines appears in Health and Safety Code Sections 43151 through 43153. As stated in 43151(a):

> "No person who is a resident of, or who operates an established place of business within, this state shall import, deliver, purchase, rent, lease, acquire, or receive a new motor vehicle, new motor vehicle engine, or motor vehicle with a new motor vehicle engine for use, registration, or resale in this state unless such motor vehicle engine or motor vehicle has been certified pursuant to this chapter. No person shall attempt or assist in any such action." (emphasis added)

Based on this language, it would certainly appear that California-certified engines are required in all heavy-duty trucks used in California by individuals or organizations who have a "place of business" in California. 43151(d) further defines "established place of business" as "a place actually occupied either continuously or at regular periods."

Notwithstanding the above language, there are many heavy-duty trucks operated in California, by California businesses, that are not equipped with California-certified engines. This practice is defended based on the language of Section 43153 which prohibits anyone engaged in "selling", "renting or leasing" from supplying non-California certified engines to someone who does business in California, when the engines are "intended primarily for use or for registration in this state." (emphasis added)

Section 43151, which applies to users of engines, does not put a threshold value on "use" of an engine in California, but 43153, which applies to sellers of engines, seems to limit the requirement for California engines to those which are "primarily" used in California. Certain users of heavy-duty engines have asserted that, read in context, the prohibition against the use of non-California engines applies only to engines which are used "primarily" in California.

Furthermore, "primarily" can be interpreted differently by different people. Does "primarily" mean more than 50 percent? Or does "primarily" mean that California is the state where the engine receives it "prime" or principal use compared to any other state? If a California trucking firm was operating only in California, Nevada, and Arizona and accumulated 40 percent of its miles in California and 30 percent of its miles in each of the other states, would California engines be required?

In response to these and similar questions, ARB has developed an informal policy as to which heavy-duty vehicles must use California engines. This policy states that any heavy-duty vehicle registered in California, or which accumulates more than 25 percent of its annual mileage in California, must use a California-certified engine (Kayne, 1988). The registration provision is apparently intended to include both intra-state registered vehicles and those operating with California baseplates under interstate apportionment agreements (these agreements are discussed in Section Three).

Unfortunately, the implementation of this policy suffers from several problems which have rendered it essentially irrelevant for interstate trucks. First, and most serious, is the fact that it has not been communicated effectively to the truck dealer and user communities, or to DMV. None of the four truck dealers contacted during this study were aware of any such policy, nor was the California Trucking Association, nor were any of the DMV staff contacted. As a result, truck dealers are currently working under another--very different--set of policy assumptions. These are discussed in Section Four.

A second, and related problem is that the policy is not enforced. Although ARB in-use enforcement staff conduct occasional checks of truck fleets for tampering, etc., they have not inspected a diesel fleet for more than two years (Madlock, 1987). Although inspections are scheduled to resume in the near future, there are presently no plans for these inspections to include certification checks. Neither the CHP nor the DMV currently attempts to enforce this policy, being unaware of it. In addition, for reasons discussed in Section Five, this policy would be very difficult to enforce in its present form.

3.0 HEAVY-DUTY VEHICLE REGISTRATION POLICIES

Presently, the primary means of enforcing California certification and related requirements is through the registration process, administered through the Department of Motor Vehicles (DMV). This section describes the vehicle registration options for heavy-duty vehicles, the registration procedure, enforcement mechanisms, and related topics. As will become clear in the discussion which follows, these procedures do not presently provide assurance that vehicles required to be equipped with California engines are in fact so equipped. Suggestions for improvements in the procedures will be presented in Section Five.

Light-duty vehicles are registered in their state of origin, and permitted to pass freely throughout the U.S. and Canada without paying further fees or taxes. In contrast, heavy-duty trucks and buses have long been subject to a complex set of rules, regulations, and fees imposed not only by their state of registration but also by most of the other states and provinces through which they pass. In the past, this required interstate truckers to obtain permits and pay fees in nearly every state in which they operated. The cost and administrative burden involved in so doing placed a heavy burden on the trucking industry.

This complex patchwork of regulations and fees is in the process of being supplanted by interstate registration agreements for heavy-duty vehicles. These agreements typically provide either for reciprocity or for apportionment of registration fees, based on the mileage travelled within each state.

California presently maintains reciprocity agreements with 12 states, the District of Columbia, and six Canadian provinces (DMV, 1986). Vehicles bearing license plates from any of these entities may operate freely in California, and vice versa.

California is also a party to bilateral (two-state) apportionment agreements with four western states and the province of British Columbia; as well as to the International Registration Plan or IRP. The IRP is a multilateral agreement which currently includes 35 other states and the province of Alberta (several more are expected to join in the near future). Under these agreements, registration fees for trucks "baseplated" (registered) in California are shared with other states in proportion to the mileage traveled in each.

As a result of these programs, heavy-duty vehicles in California are registered in two different ways. Vehicles used in interstate commerce may register as "apportioned" vehicles subject to the agreements, while those not so used must register "in-state", in the same manner as light-duty vehicles. These two registration programs are discussed separately below.

3.1 In-State Registration

Any vehicle may be registered "in-state", in the same manner as a light-duty vehicle. This is the only registration option available to vehicles which are not engaged in interstate commerce, and the great majority of trucks registered in California are registered in this way. However, less than half of the large truck-tractors (which account for the greatest share of the emissions) are so registered (DMV, 1987). Heavy-duty vehicles registered in-state must pay special fees in order to operate in any other state or province (except for those with which California has reciprocity agreements), providing a strong incentive for trucks operating interstate to register under the IRP instead.

Registration papers for new vehicles which are to be registered in-[Bate are normally submitted to DMV by the dealer. These papers require the dealer to state that the vehicle being sold complies with California emissions standards. There is no independent verification that this is the case, however. For gasoline-powered vehicles less than 8,500 pounds GVW, a Smog Certificate must be submitted as well--providing some measure of independent verification. Heavy-duty and diesel vehicles are exempt from the Smog Certificate requirement, however.

The requirement that a vehicle be equipped with a California engine applies only to new vehicles being registered for the first time in California. A "used" vehicle equipped with a 49-state engine may legally be brought in from another state and registered, provided that its odometer shows at least 7,500 miles. This mileage represents somewhat less than one month's operating time for a typical line-haul truck. Since new trucks are typically driven, rather than carried, to the dealer's lot, they may arrive at the lot with several thousand miles on the odometer already. Thus, there is a substantial potential for abuse of this regulation, through the registration of new or nearly-new vehicles as "used".

There is some evidence that such abuse is going on. Sierra is aware of one particular case in which a new truck was registered out-of-state, then "leased" to a California business for a short time while accumulating 7,500 miles. The business then purchased it from the dealer and registered it as "used".

There is also strong indirect evidence that this may be occurring on a significant scale. A DMV report of truck registrations (DMV, 1987) provides a breakdown of registration statistics by body type. This report shows that roughly as many truck-tractors are being registered "in-state" for the first time as "used" vehicles as are being registered for the first time as "new" (DMV, 1987). The ratio of "new" registrations to first-time "used" registrations for other body types ranges from about 3.5:1 to more than 10:1. The unusually large fraction of "used" truck-tractors coming into California strongly suggests that truckers are exploiting this loophole to avoid the requirement for California engines.

3.2 Apportioned (Inter-State) Registration

California is a party to the International Registration Plan (IRP), which establishes a mechanism for "apportioning" vehicle registration fees between states in proportion to the mileage travelled in each. Under the IRP, each fleet of one or more vehicles selects a state in which to register its vehicles. This state receives the registration forms from the fleet and provides it with license plates (the vehicles are then said to be "baseplated" in that state). Vehicles baseplated in any of the 36 states and one Canadian province signatory to the IRP agreement may then operate freely throughout all of them. In the same way, California-baseplated vehicles may operate freely in any of the four states and one province with which California has bilateral proration agreements.

Fleets are required to keep track of their mileage within each state, and to report the totals for each year with their annual registration renewal. The totals are then used to determine each state's pro-rata share of the registration fees for that fleet. The motor vehicle department in the state which receives the registration then distributes the fees (with copies of the mileage reports) to each of the other member states in which that fleet operated.

Presently, about 37,000 vehicles are baseplated in California under the IRP program. Of these, roughly 26,000 are truck-tractors, 10,000 are single-unit van trucks, and 560 are buses. In addition, about 76,000 non-California baseplated vehicles (nearly all of which are truck-tractors) operate at least part of the time in California under this program (DMV, 1987).

A key feature of the IRP registration procedure is that there are no regulations which require a vehicle or a fleet to be baseplated in any particular jurisdiction. For its vehicles to be baseplated in a particular state, a fleet must maintain "place of business" there, but there is no requirement that vehicles based in or operating out of a particular state be baseplated in that state. Thus, it is quite likely that some vehicles carrying California baseplates will never actually enter the State of California, and that other vehicles may be based here their entire operating lives while being baseplated in other states.

Because of this, the California DMV presently places no emissions requirements whatsoever on vehicles registered under the apportionment program--they are not required to have even Federally certified engines. DMV does not presently inquire as to the type of emissions certification (if any) possessed by each vehicle (Wilson, 1988). It is likely that most of the trucks with apportioned registration operating in California are equipped with 49-state or (in some cases) 50-state engines. In addition, the possibility of a significant number of Canadian or other-model engines cannot be ruled out.

3.3 Registration Enforcement

Enforcement of California's motor vehicle emissions regulations is through the vehicle registration process. There are two components to this enforcement:

1. Ensuring that vehicles operating in California are properly registered here; and

2. Ensuring that vehicles which are registered here comply with California emissions regulations.

The first component is also required to ensure the collection of registration fees by the State. As a result, it has received a fair amount of attention and effort by DMV, CHP, and other agencies. In spite of this effort, however, a recent CHP report (CHP, 1987) estimates that as many as one million vehicles (5 percent of the fleet) may be operating illegally with expired registrations; in addition to an unknown number of vehicles which are improperly registered in other states. Because heavy-duty trucks are often inspected at weigh stations, registration enforcement for these vehicles is probably more effective than for light-duty cars and trucks. No estimates of the fraction of heavy-duty vehicles improperly registered are available, however.

The second component of emissions enforcement is verification that vehicles registering in California are actually in compliance with California regulations. This component is the responsibility of the Department of Motor Vehicles. While DMV has invested some effort in ensuring emissions compliance for light-duty vehicles (through the Smog Check Program), enforcement for heavy-duty vehicles has been lacking.

Since heavy-duty vehicles are not yet subject to the Smog Check, the only emissions-related requirement is that they be equipped with a properly certified engine (i.e. California-certified if registered new; and California or Federally-certified if registered as a used vehicle). As stated previously, DMV presently applies no emissions requirements whatsoever to vehicles registering under the IRP. In addition, enforcement for heavy-duty vehicles has been lax even in the in-state registration program.

For new vehicles, the registration papers submitted by the dealer are required to include a certification that the vehicle meets California emissions standards. However, DMV does not spot check or audit dealer records to confirm that this certification is true. A DMV contact stated that this is because DMV has never received any complaints from consumers on this issue (Keating, 1988). Since the effect of a dealer's violation of the regulations would be to make available to the consumer a desired engine and/or vehicle which he/she could not otherwise obtain in California, it is unlikely that he/she would complain.

Used vehicles are required to meet either California or Federal emissions standards to be registered in California. Used vehicles coming into the state are inspected at local DMV offices to confirm their identity. In the past, however, these inspections have covered emissions certification only for those vehicles subject to the Smog Check (i.e. light-duty non-diesel). Thus, there was no confirmation that used heavy-duty vehicles being registered in California were in compliance even with the Federal emissions standards. A memo correcting this practice was scheduled to go out in February, 1988. Some time will be required to actually implement the change in procedures,however.

3.4 Sales Tax Collection and Enforcement

Closely related to the issue of vehicle registration is that of collecting the sales tax due on new vehicle sales. This tax is presently collected by DMV on behalf of the State Board of Equalization. Tax is due on any new vehicle delivered within the State of California, or to a California resident or business. Vehicles delivered outside California, to persons not residing or maintaining a place of business in California, are exempt from sales tax, even when sold by a California dealer.

In addition, vehicles sold to firms engaged in interstate commerce may be exempted from California sales tax even though the purchasing firm maintains a place of business in California. For this exemption to apply, the purchaser must take physical delivery of the vehicle outside of California, and must certify that the vehicle will be used more than 50 percent outside of California for the first six months. After six months the vehicle can be used in California without restriction (Day, 1988).

These certifications are checked by the State Board of Equalization. Purchasers are required to submit documents to verify that usage was primarily out-of state. The Board occasionally audits these documents, checking the material submitted against the original logs. In addition, the Board audits all new truck dealers every three years to check that sales and taxes due are being reported correctly to the State. These audits do not presently include any checks on the certification status of the vehicles sold, but a Board of Equalization contact indicated that such checks could readily be added to the audit procedure (Day, 1988).

4.0 NEW TRUCK DEALERS: CURRENT PRACTICES AND UNDERSTANDING

Truck dealers, as the parties responsible for ordering either a California or a 49-state engine from the factory, play an important part in the application of these regulations. To gain some insight into these dealers' perceptions of the regulatory requirements and their actual practices, Sierra contacted sales personnel at four Sacramento-area heavy truck dealerships. Two contacts were made in person, and two by telephone.

In each case, the staff member responsible identified himself, and stated the purpose of the study and the fact that it was being conducted for ARB. Thus, the answers received may not have been fully accurate--especially as concerns potential illegal activity. Undercover contacts might give a more realistic picture of the situation. This would require personnel thoroughly familiar with the trucking subculture, however.

The responses received from the four dealerships showed a generally similar understanding of certification policies. All four dealerships recognized that vehicles delivered in-state, for registration in-state, required California-certified engines. Similarly, all four stated that vehicles delivered out-of-state to out-of-state purchasers (not residing or maintaining a place of business in California) could legally use 49-state engines. None of the dealers contacted was aware of the ARB policy which would require even out-of-state trucks to have California engines if they operate more than 25 percent of the time in California.

The most significant "gray area" turned up in our discussions with the dealership personnel was in the handling of sales to interstate trucking firms having a place of business in California. In this case, three of the four dealerships followed the same guidelines as for determining sales tax liability--i.e. if the truck was delivered out-of-state and the owner certified that it would be used more than 50 percent out-of-state for the first six months, then a 49-state engine would be allowed. The fourth dealership believed that a California engine would be required.

It was apparent from our discussions with the three dealerships following the "sales tax" rule that they were simply unaware of ARB's policy in this area. In contrast, all were highly aware of the Board of Equalization policy concerning sales tax liability. In this case, it would appear that the Board of Equalization has been much more effective in communicating with the dealership community than has ARB.

Our discussions with the truck dealers also touched on ways of getting around the regulations requiring a California-certified engine. There was a consensus that some cheating does occur, but only one believed (or was willing to state) that the incidence of cheating is at all significant. The simplest way to cheat would be outright falsification (i.e. certifying that the truck has a California engine when in fact it has a Federal engine). While this would result in heavy penalties if detected, the risk is fairly low, since there is presently no independent check.

Another, more sophisticated approach is to sell a new vehicle as "used": either by rolling the odometer forward to 7,500 miles or by "leasing" it out-of-state (usually to the purchaser) for a short time before selling it. Since a typical line-haul truck will accumulate the 7,500 miles required to qualify as a "used" vehicle in less than a month, it is even conceivable that the vehicle could operate with temporary plates during this "break-in" period.

All of the dealership personnel contacted denied that <u>their</u> dealership engaged in such activities, but the agreed that these do occur, and one person claimed specific knowledge of such occurrences at another dealership (this claim is corroborated by some information available to Sierra as well). Thus, it can be concluded that some cheating in this area does occur, but the extent and significance of this cheating cannot be assessed from our present data.

5.0 ANALYSIS AND RECOMMENDATIONS

As the foregoing discussion makes clear, the present program for enforcing the use of California-certified engines in heavy-duty trucks and buses used in California contains some significant loopholes and deficiencies, especially where interstate trucks are concerned. It is not clear that any significant effort to improve this situation would be warranted, however, since - unless EPA or ARB revise their future emission standards - the entire issue will become moot after 1989. If at some future time the ARB and EPA emissions standards are again different, then the question of enforcing California certification would need to be addressed. This section presents our analysis of the issues and problems involved, and presents our recommendations for policy and enforcement procedures in the event that this occurs. Since the issues for in-state registered vehicles are considerably different from those for vehicles with apportioned registration, the two cases are discussed separately below.

5.1 In-State Registration

Present policy requires that the dealer certify that the vehicle meets California emissions standards before a new vehicle can be registered as a non-apportioned vehicle in California. This policy appears to be fully workable, and - based on the evidence available - reasonably successful at present. Some modifications which could help in improving its effectiveness are the following.

1. Close the loophole allowing 49-state heavy-heavy and medium-heavy trucks to be imported as "used" after only 7,500 miles. A requirement that heavy-duty vehicles be at least two years old to qualify as "used" would effectively eliminate this problem.

2. Train DMV inspectors to check emissions equipment, or expand the Smog Check Program to require Certificates of Compliance for used heavy-duty vehicles being registered for the first time in California. For diesels, these inspections should cover the engine certification and the presence and proper functioning of all emissions controls.

3. Institute procedures for confirming that vehicles certified by the dealer as meeting California standards actually do so. This could include periodic audits of dealers, cross-checking of engine serial numbers against manufacturer's data, or a requirement that the manufacturer supply a special certificate, which would be sent in by the dealer with the registration application.

4. Conduct a field study to determine whether any significant number of California intra-state vehicles are operating with improper registration (out-of-state or apportioned plates). Institute appropriate enforcement actions if so.

5.2 Apportioned Registration

Current policy

Trucks with apportioned registration include both those with California baseplates and those with non-California baseplates which operate in California. Present ARB policy requires all trucks with California baseplates to use California engines. This policy is not presently enforced by DMV, however (in fact, trucks need not even have Federally-certified engines to register under the IRP). In addition, ARB has considered a policy to require trucks registered outside the state, but which accumulate at least 25 percent of their mileage in California to use California engines as well. This policy has not yet been formalized.

Because of the special nature of the IRP, the application of registration enforcement programs to vehicles with apportioned registration is very difficult, and is likely to result in unforeseen and undesirable consequences. Since the state of registration is chosen as a matter of convenience,. any attempt by DMV to enforce ARB's current policy of requiring California engines would simply result in truck owners choosing to baseplate other states, with no benefit to air quality.

Application of the "25 percent" policy now under consideration would be likely to result in some increase in the use of California engines, but would have the undesirable effect of placing smaller local and regional shipping lines based in California at a disadvantage with respect to the larger national lines. These local and regional lines would have to purchase California engines, while the larger national lines could arrange to shuffle trucks in and out of California in such a way that no single truck accumulated more than 25 percent of its mileage there. The ability of the large national shipping lines to hold each trucks mileage in California below 25 percent would significantly reduce the potential air-quality benefits from this approach.

The application and enforcement procedures for the 25-percent policy are also somewhat problematic. Under current statute, this requirement could apply only to new vehicles. Thus, truck owners would be required to estimate at the time of purchase what fraction of each truck's time would be spent in California. This would be difficult both to do and to enforce. This would also introduce a strong incentive to use only older trucks in California. Since older trucks are likely to have higher emissions, this could well have a net negative effect on air quality.

Limitations of the current law

A strict reading of Section 43151(a) would prohibit any person residing or having a place of business in California from purchasing any new vehicle or engine anywhere which was not California-certified. Since California has no jurisdiction over purchases in other states, however, the most that could be accomplished would be to prohibit such vehicles from entering California. While no such policy has been proposed, its potential effects are worth examining, as they reveal the shortcomings of the current law.

Strict enforcement of Section 43151(a) would introduce a strong incentive for trucking companies not to maintain a "place of business" in California, since truck purchases by companies without a place of business would be unrestricted. This would likely lead to a proliferation of specialist "terminal" companies to replace the shippers' own depots. These companies might provide truck loading, warehousing, truck maintenance, etc. while operating no trucks of their own. In addition, since the law applies only to new vehicle purchases, it would provide an incentive to purchase vehicles used. "Laundering" of vehicle purchases by taking delivery out-of-state and operating them for the minimum 7,500 miles could become common. Application of the two-year minimum rule suggested above would eliminate this problem, but would lead to an even greater concentration of older trucks in California.

Recommended approach

To be effective, any policy for encouraging the use of California-certified engines in interstate trucks operating in California must take into account the special characteristics of this type of operation. It should provide for the maximum feasible use of California engines in California-based trucks, while preferably avoiding the introduction of competitive distortions or incentives for "shuffling" trucks from depot to depot. In particular, it should avoid distinguishing between vehicles purchased new and those purchased used.

To avoid undue interference with interstate commerce, it is desirable that California's policy allow for occasional deliveries into the state by trucks with Federal engines. For maximum environmental benefit, however, it should attempt to minimize such deliveries. Finally, to be politically and administratively feasible, the policy must be relatively simple, compatible with the structure of the Interstate Registration Plan, and enforceable using available information.

The following paragraphs outline a policy and enforcement procedure which we believe could fulfil these requirements. Sierra's recommended policy would apply to vehicle fleets rather than to individual vehicles, since fleets are the units of registration under the IRP. This policy would be to require fleets traveling more than about one million miles (or 50 percent of their total miles, whichever is less) in California to ensure that at least 80 percent of those miles are travelled by vehicles having California engines. The specific mileage threshold and percentages cited are based on the following rationale:

- Fleets which accumulate 50 percent of their total miles in the state are clearly used primarily in California. These vehicles must be covered by California-certified engine requirements to maintain consistency with the current statutory framework.

- Fleets which travel more than one million miles in California are significant contributors to air pollution and are unlikely to be owned by small businesses that would be strained by additional air pollution control requirements. They are also likely to have a base or place of business within California.

- Although a requirement for 100 percent of California VMT to be accumulated using California-certified engines could be pursued without necessarily infringing on interstate commerce, allowing some fraction of miles to be accumulated with 49-state engines would eliminate arguments that 100 percent use of California engines would be impractical. By providing added flexibility, that would also reduce the motivation to cheat.

We would expect these proposed values to be discussed in detail in the course of any future regulatory or legislative action in this area.

One million miles is about the annual mileage accumulation for a 5 to 10 truck fleet. Thus, this criterion would include essentially all medium-and large-sized truck fleets based in or doing significant business in California. At the same time, the 50 percent criterion would include the smaller fleets based in or having a major portion of their operations in the state. These criteria would exclude most small out-of-state fleets not having bases in California, however. The requirement that 80 percent (rather than 100 percent) of the miles for the affected fleets be on California engines is intended to allow fleet managers some flexibility in scheduling (e.g. for shipments coming in from out-of-state), while retaining most of the benefits of requiring California engines.

Enforcement of this approach could be done through the existing IRP registration process. Truck fleets are required to report their total miles of operation and the fraction of total mileage in each state to the state in which they are baseplated. California receives a copy of each report for fleets operating in California, along with its pro-rata share of the registration fees. From these reports, it would be straightforward to identify fleets subject to the 80 percent rule.

A letter could then be sent to the manager of each affected fleet, requiring him to break down the California mileage reported between California and Federal engines. Non-responsive fleets, or fleets not maintaining the required percentage of travel by California engines, would be listed in the CHP's computers, and could be cited or denied entry to California at weigh stations and border checkpoints (in practice, some sort of non-conformance penalty for minor violations of the requirement might be desirable). Honest reporting would be confirmed by occasional audits, just as the DMV now audits the total mileage reports submitted.

The basic structure outlined above appears to be administratively feasible, and would require minimal changes to the present system of registration under the IRP. A statutory change would be needed, however, to authorize ARB to require California engines on vehicles in-use, rather than just new vehicles as at present. Although we are not aware of any specific problems, a legal analysis would also be needed to determine whether such an approach would be compatible with California's obligations under the IRP agreement, and - if not - what modifications to the agreement would be required.

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SECTION III

A STUDY OF EXCESS MOTOR VEHICLE EMISSIONS

THE FEASIBILITY OF A HEAVY-DUTY GASOLINE TRUCK INSPECTION AND MAINTENANCE PROGRAM

FINAL REPORT

ARB Contract No. A5-188-32

Prepared for:

California Air Resources Board
P.O. Box 2815
Sacramento, CA 95812

Prepared by:

Radian Corporation
10395 Old Placerville Road
Sacramento, CA 95827

December 1988

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EXECUTIVE SUMMARY

Inspection and maintenance (I/M) programs have been adopted by a number of states, including California, to improve the level of emissions control for motor vehicles in consumer use. Under California's Smog Check Program, light-duty cars and trucks garaged in most urban areas in the state are required to be inspected and to have their emissions checked every two years. In this study, Radian Corporation and Sierra Research examined the feasibility and cost-effectiveness of including heavy-duty gasoline vehicles in the Smog Check Program.

Heavy-duty gasoline trucks can be divided into two classes: light heavy-duty, ranging from 8,500 to about 16,000 lb. gross vehicle weight (GVW); and medium heavy-duty, ranging from 16,001 to about 50,000 lb. GVW. Trucks under 8,500 lb. are classified as light-duty vehicles, while those over 50,000 lb. are almost entirely diesel powered. Estimates of the potential emission reductions due to a periodic I/M program for heavy-duty gasoline trucks were developed separately for the medium and light heavy-duty classes.

Radian estimated the reduction in emissions due to a heavy-duty I/M program by estimating the I/M failure rate, the reduction in emissions due to repairs of failed vehicles, and the resulting reduction in fleet-average emission factors. These were multiplied by total vehicle miles travelled (VMT) to give the statewide emissions reduction. Program cost-effectiveness was calculated by estimating the total costs of inspections, repairs, and Smog Certificates under the program, and dividing this by the emissions reduction. Half of the program cost was allocated to HC reductions and half to CO; the small NO_x reduction projected was treated as a free benefit.

The scarcity of data quantifying the emissions of in-use heavy-duty gasoline vehicles made it difficult to derive emission factors. This study relied on the emission factors for heavy-duty trucks which are used by both the EPA and ARB. Estimates of the I/M failure rate for heavy-duty gasoline

vehicles, and of the emission reduction due to repair of failed vehicles were based on heavy-duty gasoline vehicle data when applicable data were available, and on light-duty vehicle data when they were not. The growth in average annual vehicle miles travelled by light and medium heavy-duty gasoline trucks was estimated with the use of CalTrans data.

Emission reduction and cost-effectiveness estimates were prepared for two future years: 1988 (estimated as the first year such a program could be in effect) and 1995. The results of the analysis for 1988 are summarized in Table E-1; those for 1995 are in Table E-2. As these tables indicate, the CO reduction estimated for medium heavy-duty vehicles is significantly greater than for the light heavy-duty class. The HC emission reductions show the same trend. The total costs of an I/M program for medium heavy-duty vehicles are also significantly lower, due to the smaller number of vehicles involved. Implementing an I/M program only for medium heavy-duty trucks would be the most cost effective method to reduce emissions from the heavy-duty fleet. However, the incremental cost-effectiveness of I/M for light heavy-duty gasoline trucks still compares very favorably with the cost-effectiveness of the current Smog Check Program.

The estimates in Tables E-1 and E-2 were based on assumed I/M failure rates and emissions reductions due to repairs. The assumptions used were based on existing I/M program data wherever possible, and they are considered fairly robust. In addition, the program was given no credit for potential emission reductions due to reduced tampering and pre-inspection repairs because of the program, or for reductions in evaporative emissions due to repair of evaporative control systems. The assumptions made are thus--if anything--probably somewhat conservative.

In order to assess the sensitivity of the results to our assumptions, Radian calculated the cost-effectiveness and emission reductions which would result if the actual failure rates and emission reductions due to repair were each only 70% as great as had been estimated. The results of these

TABLE E-1. 1988 COST-EFFECTIVENESS ANALYSIS

LIGHT HEAVY-DUTY VEHICLES		
PROGRAM COST		\$4,300,000
EMISSION REDUCTION		
	HC	3.5 TONS/DAY
	CO	36.4 TONS/DAY
COST-EFFECTIVENESS		
	CREDIT FOR HC	\$0.85 PER POUND
	CREDIT FOR CO	\$0.08 PER POUND
MEDIUM HEAVY-DUTY VEHICLES		
PROGRAM COST		\$2,700,000
EMISSION REDUCTION		
	HC	11.3 TONS/DAY
	CO	175.0 TONS/DAY
COST-EFFECTIVENESS		
	CREDIT FOR HC	\$0.16 PER POUND
	CREDIT FOR CO	\$0.01 PER POUND
COMBINED LIGHT AND MEDIUM HEAVY-DUTY VEHICLES		
PROGRAM COST		\$7,000,000
EMISSION REDUCTION		
	HC	14.8 TONS/DAY
	CO	211.4 TONS/DAY
COST-EFFECTIVENESS		
	HC	\$0.33 PER POUND
	CO	\$0.02 PER POUND

TABLE E-2. 1995 COST-EFFECTIVENESS ANALYSIS

LIGHT HEAVY-DUTY VEHICLES		
PROGRAM COST		$4,600,000
EMISSION REDUCTION		
	HC	2.1 TONS/DAY
	CO	23.1 TONS/DAY
COST-EFFECTIVENESS		
	CREDIT FOR HC	$1.48 PER POUND
	CREDIT FOR CO	$0.14 PER POUND
MEDIUM HEAVY-DUTY VEHICLES		
PROGRAM COST		$2,550,000
EMISSION REDUCTION		
	HC	7.0 TONS/DAY
	CO	93.9 TONS/DAY
COST-EFFECTIVENESS		
	CREDIT FOR HC	$0.25 PER POUND
	CREDIT FOR CO	$0.02 PER POUND
COMBINED LIGHT AND MEDIUM HEAVY-DUTY VEHICLES		
PROGRAM COST		$7,150,000
EMISSION REDUCTION		
	HC	9.1 TONS/DAY
	CO	117.0 TONS/DAY
COST-EFFECTIVENESS		
	CREDIT FOR HC	$0.54 PER POUND
	CREDIT FOR CO	$0.04 PER POUND

calculations are shown in Table E-3. Under these alternative assumptions, the emissions benefits would be roughly halved, and the cost per pound of emissions eliminated would double. The resulting cost-effectiveness values still compare favorably with those for the existing Smog Check Program, however.

To assess the feasibility of including heavy-duty gasoline trucks in the Smog Check Program, Radian conducted a telephone survey of Smog Check stations and heavy-duty truck repair shops in California. The survey determined their interest in the program and whether they had the physical capacity (e.g. space, door clearances, etc.) to be able to perform Smog Checks on heavy-duty vehicles. Eighty-four percent of the Smog Check stations surveyed indicated they would be interested in performing Smog Checks on heavy-duty gasoline vehicles. The same percentage of the Smog Check stations also believed they had adequate space to Smog Check heavy-duty gasoline trucks. The heavy-duty truck repair stations surveyed were not interested in performing Smog Checks on heavy-duty vehicles.

No major modifications would be required to the current Test Analyzer System for it to be used with heavy-duty gasoline trucks. The software currently has the capability of determining that the vehicle being tested is a heavy-duty gasoline truck as opposed to a light-duty vehicle. The only modifications required would be the addition of a standardized menu for the make of heavy-duty gasoline truck, and the addition of cutpoints for the heavy-duty fleet.

The heavy-duty gasoline fleet will consist of approximately 400,000 vehicles in 1988. The light-duty vehicle fleet will consist of approximately 15,000,000 vehicles in the same year. The addition of the heavy-duty gasoline fleet to the I/M program will increase the total number of vehicles subject to the "Smog Check" by 3 percent.

The majority of repairs performed on heavy-duty gasoline trucks to maintain or improve their engine/emission systems would exceed $50.00. If the

TABLE E-3. EFFECT OF PESSIMISTIC ASSUMPTIONS ON I/M EFFECTIVENESS ON EMISSION REDUCTION AND COST-EFFECTIVENESS ESTIMATES

	Emission Reduction		Program Cost	Cost-Effectiveness	
	HC (tons/day)	CO (tons/day)	($/yr)	HC ($/lb)	CO ($/lb)
1988					
Base estimate	14.32	211.36	$7,000,000	$0.33	$0.02
Pessimistic estimate*	7.30	103.66	$6,400,000	$0.60	$0.04
% Change	-49%	-51%	-8.5%	+82%	+86%
1995					
Base estimate	9.12	116.99	$7,150,000	$0.54	$0.04
Pessimistic estimate*	4.49	57.42	$6,500,000	$0.99	$0.08
% Change	-51%	-51%	-9.1%	+83%	+100%

* Assumes failure rates and repair effectiveness each 70% as great as base estimate.

cost ceiling were set to $100.00 then more repairs could be successfully completed on the heavy-duty gasoline trucks. If tampering is found on a heavy-duty truck, the cost ceiling should be waived for repairing the tampered part.

The enforcement of the program could be done similarly to the light-duty vehicle program. Requiring the heavy-duty vehicle owner to produce a certificate of conformance when registering the vehicle should be a sufficient enforcement procedure.

TABLE OF CONTENTS

RADIAN CORPORATION

TABLE OF CONTENTS (Continued)

RADIAN CORPORATION

LIST OF TABLES

LIST OF TABLES (Continued)

LIST OF TABLES (Continued)

1.0 INTRODUCTION

In order to protect and improve the quality of its air, the State of California is interested in minimizing the excess pollutants from motor vehicles, including heavy-duty trucks. Inspection and maintenance (I/M) programs have been adopted by a number of states, including California, to improve the level of emissions control for motor vehicles in consumer use. Under California's Smog Check Program, light-duty cars and trucks garaged in most urban areas in the state are required to be inspected and to have their emissions checked every two years. Vehicles showing excessive emissions, or on which emissions control equipment is found to be missing, malfunctioning, or to have been tampered with are required to be repaired.

California also maintains an older inspection and maintenance program based on change of ownership. This program applies to all light and heavy-duty gasoline vehicles, including those garaged outside the major urban areas. Some other states, including Alaska and Arizona, have included heavy-duty gasoline trucks in periodic inspection and maintenance programs such as the Smog Check Program. In order to further reduce emissions from heavy-duty gasoline vehicles, California is interested in including these heavy-duty vehicles in the Smog Check Program as well. Radian Corporation and Sierra Research were commissioned by the California Air Resources Board (ARB) to examine the feasibility of including heavy-duty gasoline vehicles in the Smog Check Program.

Heavy-duty gasoline vehicles (HDGVs) are major emitters of unburned hydrocarbons (HC) and carbon monoxide (CO). These vehicles also emit lesser (but still significant) quantities of oxides of nitrogen (NOx). Historically, HDGVs have been subjected to much less stringent emissions controls than have light-duty vehicles (LDVs) such as passenger cars and light trucks. Stringent LDV emissions standards have forced the use of oxidation catalysts on most LDVs since 1975, and of "3-way" reduction/oxidation catalysts since 1981. Up through 1986, however, heavy-duty vehicles have not required catalytic converters to meet their less stringent regulations.

New Federal emissions standards taking effect in 1987 will force the use of catalytic converters on most new light heavy-duty gasoline vehicles (those with gross vehicle weights less than 14,000 lb). With the use of these sophisticated devices, and the possibility of their failure and/or abuse, the potential for excess emissions from HDGVs (and thus the need for an I/M program) will increase.

1.1 Background Information

Most heavy-duty gasoline vehicles are trucks, and most of the remaining vehicles (school buses, motor homes) are specialty vehicles built on truck chassis. The widely-used Motor Vehicle Manufacturers Association (MVMA) classification system divides trucks into eight classes, according to the manufacturers rated gross vehicle weight. For regulatory purposes, however, EPA and ARB classify vehicles only as light-duty, medium-duty, or heavy-duty. The heavy-duty classification is further subdivided into light-heavy, medium-heavy, and heavy-heavy subcategories. Table 1-1 shows these classifications.

As table 1-1 indicates, trucks with rated gross vehicle weights (GVW) of less than 6,000 lbs. are considered light-duty trucks, while those with rated GVW between 6,001 and 8,500 lbs. are considered medium-duty vehicles. Both of these classes are included in the current Smog Check Program. Trucks with rated gross vehicle weights greater than 8,501 lbs. are classified as heavy-duty vehicles. Light heavy-duty vehicles are those in MVMA classes 2b, 3, and 4. These are primarily large pickups, vans, and specialty vehicles built on pickup or van chassis, and are technically similar to light-duty vehicles. The medium heavy-duty class includes MVMA classes 5 through 7 and the lighter part of class 8 (group 1). This class includes school buses, and most single-unit trucks. Heavy heavy-duty vehicles are those over 50,000 lb. GVW, and are mostly tractor-trailer and double-trailer rigs.

Heavy heavy-duty vehicles are used for long-distance freight transport and heavy hauling. The vehicles in this classification are almost

TABLE 1-1. MVMA CLASSIFICATIONS

MMVA Class	Rated Gross Vehicle Weight (GVW, lbs)	Classification
1	0-6000	Light-Duty Vehicle
2a	6,001-8,500	Medium-Duty Vehicle
2b	8,501-10,000	Light Heavy-Duty
3	10,001-14,000	Light Heavy-Duty
4	14,001-16,000	Light Heavy-Duty
5	16,001-19,500	Medium Heavy-Duty
6	19,501-26,000	Medium Heavy-Duty
7	26,001-33,000	Medium Heavy-Duty
8, Group 1	33,001-50,000	Medium Heavy-Duty
8, Group 2	50,001-80,000	Heavy Heavy-Duty

entirely diesel powered and will not be included in this study. The medium heavy-duty class was primarily gasoline powered, but is slowly being converted to diesel power. Until recently, the light heavy-duty class was exclusively gasoline-powered, but an increasing number of diesel vehicles are being introduced in this class as well.

The dieselization of these classes is occurring for a number of reasons. Recently, diesel engines have been developed specifically for use in light and medium heavy-duty vehicles. As the emission regulations for heavy-duty gasoline engines have become more stringent, many individuals feel these standards have reduced the efficiency and durability of gasoline-powered heavy-duty vehicles. Because of perceived advantages in durability, fuel economy, and maintenance costs, diesel-powered vehicles are beginning to increase their sales fraction in the light and medium heavy-duty vehicle classes.

Emissions Regulations for Heavy-Duty Gasoline Engines

Engines used in heavy-duty vehicles are regulated separately from the vehicle itself. Once the engine is certified as complying with regulations, it can be used in any GVW class of heavy-duty truck. Emissions are measured while operating the engine over a specified test cycle on an engine dynamometer. The work done by the engine during the test is also measured. The emissions from the engine are reported in grams of pollutant per unit of work done (gm/BHP-hr). The emission standards for heavy-duty gasoline truck engines are specified in gm/BHP-hr.

Since emissions data for heavy-duty gasoline engines is typically reported in gm/BHP-hr and not gm/mi, these data cannot be used directly to calculate and predict the emissions from the heavy-duty truck fleet. In order to use the emission data generated from the engine dynamometer, the data must be converted to grams of pollutant per mile of vehicle travel. To do so, the work required to move the heavy-duty truck per mile travelled needs to be known. The work required to move the truck one mile (BHP-hr/mile) is known as the conversion factor. It is different for each size class of heavy-duty trucks.

1.2 Technical Approach

Estimates of the emission reductions due to implementing a periodic I/M program for heavy-duty gasoline trucks (HDGT) were developed separately for the light and medium heavy-duty gasoline truck categories. These reductions were estimated by combining estimates of current in-use emission factors for the heavy-duty gasoline truck fleet, the I/M failure rate that would be experienced by these vehicles, the reduction in emissions from failed vehicles due to repair, and the average annual VMT for each category.

The scarcity of data quantifying the emissions of in-use heavy-duty gasoline vehicles made it difficult to derive emission factors. This study relied on the emission factors for heavy-duty trucks which are used by both the EPA and the ARB. These values are based on estimates prepared by the EPA staff, based on a limited number of engine dynamometer tests. Deterioration rates for the heavy-duty gasoline truck fleet were calculated using light-duty vehicle deterioration rates as the basis. These may or may not be representative. The HDGV emission factors used were initially reported in gm/BHP-hr (EEA, 1985). These factors were then converted into gm/mi using conversion factors developed by EPA (Smith, 1984).

Estimates of the I/M failure rate for heavy-duty gasoline vehicles, and of the reduction in emissions from failed vehicles due to repair were based on HDGT data when applicable data were available, and on LDV data where they were not. Data for pre-1979 HDGTs came from a Radian Corporation study in New York, done in 1981. The data from this study were used to estimate I/M failure rates and emission reductions for 1974 and earlier model California HDGTs (emission controls were required earlier on California than on Federal engines). For 1975 and later model trucks, surrogate data from LDV I/M programs (for cars with similar emissions controls) were used to estimate the emission reductions due to repair. I/M failure rates for these years were estimated from failure rates in the Anchorage, Alaska HDGT I/M program. Failure rates from the Portland HDGT I/M program were also reviewed.

The average annual vehicle miles travelled (VMT) by light and medium-heavy gasoline trucks were estimated with the use of two different data sources. In 1983 a study was undertaken to estimate the average daily vehicle miles travelled (DVMT) of the heavy-duty truck fleet (Pacific Environmental Services, 1985). The results of this study were used to establish base-year VMT. Future growth in VMT, and the breakdown of total VMT by model year, were calculated using data from the CalTrans transportation planning model (California Department of Transportation, 1986).

To assess the feasibility of including heavy-duty gasoline trucks in the Smog Check Program, Radian conducted a telephone survey of Smog Check stations and heavy-duty truck repair shops in California. The survey determined their interest in the program, and whether they had physical capacity (e.g. space, door clearances, etc.) to be able to perform Smog Checks on heavy-duty vehicles. This survey also requested data on labor rates charged for heavy-duty vehicle repairs. These data, along with industry time guides and other sources, were used to calculate typical repair costs. The cost-effectiveness (cost per pound of pollutant eliminated) of extending the Smog Check Program to heavy-duty vehicles was also estimated. In addition, Radian and Sierra examined the specifications for the existing TAS analyzers used in the Smog Check Program to determine what hardware and software modifications would be required.

1.3 Limitations and Caveats

The estimates of baseline emissions and of the emissions reductions due to repair of failed vehicles are based on limited data, not all of which may be fully applicable. Estimates of the average cost of repairs are also quite uncertain, given the limited data available on I/M for these vehicles.

For light-duty vehicles, extensive (and expensive) studies have been undertaken by EPA and ARB to measure I/M program effectiveness and the reduction in emissions which could be expected. Only one such study has been undertaken to date for heavy-duty vehicles, and that study (performed by Radian in 1981) included only 1978 and older trucks. Thus, the estimates presented here, while based on the best data available, can be considered only approximate.

1.4 Outline of the Report

Section Two presents our estimates of the emission reductions which would result from a HDGT I/M program. Discussion of the base emission factors used, expected failure rates, improvements in emissions due to repairs, and the fleet reduction in emissions due to I/M can be found in this section. Section Three discusses the feasibility of implementing an I/M program for HDGTs. The results of Radian's survey of Smog Check stations, heavy-duty truck repair facilities, and heavy-duty fleet operators are presented in this section. Estimated repair costs, changes to the Test Analyzer System, and the cost-effectiveness of a HDGT I/M program are also discussed in Section Three. Section Four reviews the administrative issues, implementing the changes to the TAS, determining the emission standards, cost limits, and enforcement of the HDGT I/M program.

2.0 ASSESSMENT OF POTENTIAL EMISSION REDUCTIONS

This section presents the methodology and data used to predict the potential emission reduction due to the implementation of an I/M program for heavy-duty gasoline vehicles. The approach used to predict the emission reduction is described first. The specific data used in calculating the emission reduction are then discussed. Finally, the results of these calculations are presented and discussed.

ıhe methodology used to predict the potential emission reduction is straightforward. The following four general types of data are required:

- emission factor data (grams/mile) for the present and future HDGV fleets;
- estimates of the I/M failure rate that would be experienced by these fleets if an I/M program were instituted;
- estimates of the percentage reduction in exhaust emissions from failed vehicles due to repair; and
- the total vehicle miles travelled per year.

Estimates of the I/M failure rate and the emission reduction from repair are combined to determine the percentage reduction in fleet-average emissions due to the I/M program. When combined with the emission factor, the percentage reduction is converted to a gram/mile reduction. Finally, the truck VMT is used to estimate the total mass reduction in emissions. No attempt is made to account for the deterrent effects of the program or for effects on evaporative emissions. Given the level of technology involved, these effects are considered to be small.

2.1 Emission Factors For Heavy-Duty Gasoline Trucks

EPA estimates of the HDGT emission rates were used for this analysis (Energy and Environmental Analysis, January, 1985). In EPA's analysis, average emissions are considered to increase linearly with accumulated mileage. The EPA estimates consist of a zero mile rate and a deterioration factor, which are the intercept and the slope, respectively, of the emissions line. Table 2-1 lists the zero mile rate and deterioration factor used for each model year in calculating the emission reduction for 1988.

California began regulating emissions from HDVs in 1973. The regulations for model years 1973 and 1974 were exactly the same; however, the values for the zero mile emission rate and deterioration factor published by ARB (California Air Resources Board, 1986) are not the same for these two years. It would seem that these values should be the same, or quite similar. At ARB's request, however, Radian used the ARB values for this study.

Table 2-1 also shows the accumulated vehicle mileage assumed for each model year. The mileage data was obtained from ARB's EMFAC7C model (California Air Resources Board, 1986). These estimates were used to calculate the emission rates for each model year in calendar year 1988. Table 2-2 lists the emission rates calculated for each model year.

The emission rates shown in Table 2-2 are given in work-specific units of gm/BHP-hr. Before these data can be used to predict the emissions of the HDGT fleet they need to be converted into gm/mi. This is done by multiplying them by the conversion factor (work required per mile) for each class of heavy-duty gasoline trucks.

Conversion Factor Calculation

In this study, the heavy-duty gasoline fleet is segregated into light and medium heavy-duty categories. Conversion factors, however, are developed

TABLE 2-1. DATA USED TO CALCULATE 1988 EMISSION FACTORS FOR HEAVY-DUTY GASOLINE TRUCKS

Model Year	ZERO MILE (gm/BHP-hr) HC	CO	NOx	DETERIORATION FACTOR (gm/BHP-hr/10,000 mi) HC	CO	NOx	AVERAGE MILEAGE ACCUMULATED BY MODEL YEAR
1967	12.74	155.18	6.08	0.24	3.72	0	222000
1968	12.74	155.18	6.08	0.24	3.72	0	222000
1969	6.76	115.4	5	0.18	4.69	0.06	222000
1970	6.76	115.4	5	0.18	4.69	0.06	215000
1971	6.76	115.4	5	0.18	4.69	0.06	208000
1972	6.76	115.4	5	0.18	4.69	0.06	200000
1973	6.76	115.4	5	0.18	4.69	0.06	193000
1974	5.91	101	5	0.18	4.69	0.06	185000
1975	5.91	101	5	0.18	4.69	0.06	178000
1976	5.91	101	5	0.18	4.69	0.06	171000
1977	3	80	5	0.18	4.69	0.06	163000
1978	3	80	5	0.18	4.69	0.06	156000
1979	3	80	5	0.18	4.69	0.06	149000
1980	3	80	5	0.18	4.69	0.06	139000
1981	3	80	5	0.18	4.69	0.06	129000
1982	3	80	5	0.18	4.69	0.06	117000
1983	3	80	5	0.18	4.69	0.06	106000
1984	2.5	60	4.4	0.18	4.69	0.06	90500
1985	2.5	60	4.4	0.13	2.06	0.06	75400
1986	2.5	60	4.4	0.13	2.06	0.06	57400
1987	2.5	60	4.4	0.13	2.06	0.06	39400
1988	2.5	60	4.4	0.13	2.06	0.06	19700

TABLE 2-2. HEAVY-DUTY GASOLINE TRUCK EMISSION RATES FOR 1988

Model Year	(gm/BHP-hr) HC	CO	NOx
1967	18.07	237.76	6.08
1968	18.07	237.76	6.08
1969	10.76	219.52	6.33
1970	10.63	216.24	6.29
1971	10.50	212.95	6.25
1972	10.36	209.20	6.20
1973	10.23	205.92	6.16
1974	9.24	187.77	6.11
1975	9.11	184.48	6.07
1976	8.99	181.20	6.03
1977	5.93	156.45	5.98
1978	5.81	153.16	5.94
1979	5.68	149.88	5.89
1980	5.50	145.19	5.83
1981	5.32	140.50	5.77
1982	5.11	134.87	5.70
1983	4.91	129.71	5.64
1984	4.13	102.44	4.94
1985	3.48	75.53	4.85
1986	3.25	71.82	4.74
1987	3.01	68.12	4.64
1988	2.76	64.06	4.52

for each specific truck class (i.e., Class 2b through Class 8). To calculate emission factors for the light and medium heavy-duty categories, the conversion factors for each class had to be aggregated into their respective category, light or medium. These aggregated conversion factors were calculated for each model year.

Relative VMT and sales fraction data were used to calculate an aggregate conversion factor for each model year category. Since the available VMT data were category specific (light and medium heavy-duty) and not class specific (2b, 3, etc.), the class average VMT values were included in the conversion factor calculation. A similar weighting was used to account for the difference in sales fraction between the various classes. The data used to calculate the conversion factors can be found in Tables 2-3 and 2-4. Up to 1977, historical data was used to calculate class specific conversion factors (Smith, 1984).

For later model year conversion factors, estimates of the reduction in vehicle rolling resistance were used to determine the estimated reduction in the conversion factor. Table 2-4 lists the estimated percent reduction in the 1977 conversion factor for a number of subsequent years. The future conversion factors were calculated using the 1977 conversion factor as the base value. Estimates of improvements in rolling resistance were used to determine the percentage reduction in the conversion factor (Smith, August 1984). The values developed by Smith were not used since these tended to overestimate the zero mile emission factor used by the ARB. The percent reductions in the 1977 conversion factor, listed in Table 2-4, were arrived at by iteration. These values were found to result in an aggregate zero mile emission rate, for the light and medium heavy-duty truck classes, that is approximately the same as the ARB noncatalyst heavy-duty truck zero mile emission rate. Linear interpolation was used to determine the conversion factors for years not listed in table 2-4. Linear interpolation was also used to calculate historic conversion factors for years which no conversion factor data existed.

TABLE 2-3. HISTORICAL CONVERSION FACTOR DATA

Weight Class	Model Year	Relative VMT	Sales Fraction	Gas Fraction	Conversion Factor	Weighted Conversion Factor
2b	1962	11614	0.064	1.000	0.87	-
2b	1965	11614	0.080	0.998	0.87	-
2b	1967	11614	0.096	0.997	0.87	-
2b	1970	11614	0.126	0.999	0.87	-
2b	1972	11614	0.132	1.000	0.87	-
2b	1975	11614	0.280	1.000	0.87	-
2b	1977	11614	0.348	0.999	0.87	-
2b	1978	11614	0.346	1.000	0.87	-
3 - 5	1962	9832	0.446	0.966	1.16	0.590
3 - 5	1965	9832	0.382	0.975	1.19	0.592
3 - 5	1967	9832	0.305	0.969	1.20	0.490
3 - 5	1970	9832	0.225	0.997	1.22	0.435
3 - 5	1972	9832	0.216	0.997	1.24	0.434
3 - 5	1975	9832	0.106	0.995	1.19	0.252
3 - 5	1977	9832	0.071	1.000	1.15	0.245
3 - 5	1978	9832	0.130	1.000	1.13	0.416
6	1962	9734	0.252	0.958	1.38	0.390
6	1965	9734	0.235	0.895	1.44	0.401
6	1967	9734	0.287	0.906	1.48	0.527
6	1970	9734	0.283	0.924	1.53	0.632
6	1972	9734	0.304	0.969	1.57	0.747
6	1975	9734	0.335	0.959	1.60	1.021
6	1977	9734	0.245	0.900	1.57	1.026
6	1978	9734	0.202	0.894	1.56	0.792
7	1962	11223	0.102	0.569	1.57	0.122
7	1965	11223	0.094	0.553	1.60	0.128
7	1967	11223	0.096	0.621	1.64	0.155
7	1970	11223	0.100	0.667	1.68	0.204
7	1972	I1223	0.076	0.652	1.71	0.158

(Continued)

TABLE 2-3. HISTORICAL CONVERSION FACTOR DATA (Continued)

Weight Class	Model Year	Relative VMT	Sales Fraction	Gas Fraction	Conversion Factor	Weighted Conversion Factor
7	1975	11223	0.067	0.551	1.74	0.147
7	1977	11223	0.059	0.422	1.73	0.147
7	1978	11223	0.063	0.385	1.71	0.134
8	1962	18413	0.131	0.447	1.93	0.251
8	1965	16997	0.196	0.315	1.99	0.284
8	1967	16997	0.216	0.269	2.02	0.282
8	1970	16247	0.266	0.156	2.10	0.229
8	1972	15783	0.266	0.118	2.15	0.176
8	1975	15560	0.198	0.106	2.17	0.145
8	1977	15560	0.273	0.039	2.12	0.107
8	1978	15560	0.252	0.042	2.07	0.098

$$\text{Weighted conversion factor} = \frac{\text{conversion factor} \times (GF \times SF) \times VMT}{\sum_{i=3}^{8} [(GF_i \times SF_i) \times VMT_i]_{\text{for model year = constant}}}$$

TABLE 2-4. FUTURE CLASS CONVERSION FACTOR DATA
Percent Improvement
(Base Year 1977)

Model Year	Light Heavy-Duty Improvement	Medium Heavy-Duty Improvement
1982	15	13
1987	16	14
1992	17	15
1997	18	16

The conversion factor for the light HDGT fleet was calculated using the conversion factor data for class 2b trucks (Smith, 1984). Smith aggregated the data for class 3 and 4 trucks (which are also counted as light heavy-duty vehicles) with that for class 5 (which is classed as medium heavy). Since the sales and populations of class 3 and 4 trucks are small compared to those for either class 2b or class 5, this inconsistency was considered to be negligible. With this assumption, the conversion factor for the light HDGT fleet can be taken as equal to that for class 2b trucks. Tables 2-5 and 2-6 list the conversion factors calculated for both the light and medium HDGT fleet for model years 1962 through 1997.

The conversion factor for the medium heavy-duty gasoline truck fleet was calculated using data for class 3 through 8 gasoline trucks. The influence of truck class on the conversion factor can be seen in Table 2-3. The different classes constituting the medium HDGT fleet have significantly different conversion factors. In order to obtain an average conversion factor for a given model year, the conversion factors for each MVMA class were weighted by the relative VMT and sales fraction for that class. The relative VMT and sales fraction data used to weight the conversion factors are given in Table 2-3. The relative VMT data in the table came from the 1977 Truck Inventory and Use Survey (Smith, 1984). The weighted conversion factor column in that table shows each class's contribution to the average. Summing the weighted conversion factors for a given model year gives the average conversion factor for that model year.

Given the work-specific emission factors in Table 2-2, and the conversion factors in Tables 2-5 and 2-6, it is possible to calculate emission factors in grams per mile. Tables 2-7 and 2-8 list the emission factors calculated for the light and medium HDGT fleets respectively. The light heavy-duty emission factors for 1987 and 1988 are the same as the ARB factors for heavy-duty trucks that use catalysts. These values were used since it is expected that a significant portion of this fleet will be equipped with oxidizing catalysts beginning in 1987.

TABLE 2-5. HISTORICAL CLASS CONVERSION FACTORS

Model Year	Light Heavy-Duty Conversion Factor	Medium Heavy-Duty Conversion Factor
1962	0.87	1.35
1963	0.87	1.37
1964	0.87	1.39
1965	0.87	1.40
1966	0.87	1.43
1967	0.87	1.45
1968	0.87	1.47
1969	0.87	1.48
1970	0.87	1.50
1971	0.87	1.51
1972	0.87	1.51
1973	0.87	1.53
1974	0.87	1.55
1975	0.87	1.56
1976	0.87	1.54
1977	0.87	1.52

TABLE 2-6. FUTURE CLASS CONVERSION FACTORS

Model Year	Light Heavy-Duty Conversion Factor	Medium Heavy-Duty Conversion Factor
1978	0.847	1.49
1979	0.825	1.45
1980	0.802	1.42
1981	0.779	1.38
1982	0.757	1.35
1983	0.755	1.35
1984	0.754	1.34
1985	0.753	1.34
1986	0.751	1.34
1987	0.750	1.34
1988	0.749	1.33
1989	0.747	1.33
1990	0.746	1.33
1991	0.745	1.33
1992	0.744	1.33
1993	0.742	1.32
1994	0.741	1.32
1995	0.740	1.32
1996	0.739	1.32
1997	0.737	1.31

TABLE 2-7. LIGHT HEAVY-DUTY GASOLINE TRUCK EMISSION FACTORS FOR 1988

Model Year	HC	(gm/mile) CO	NO_x
1967	15.72	206.85	5.29
1968	15.72	206.85	5.29
1969	9.36	190.98	5.51
1970	9.25	188.12	5.47
1971	9.14	185.27	5.44
1972	9.01	182.00	5.39
1973	8.90	179.15	5.36
1974	8.04	163.36	5.32
1975	7.93	160.50	5.28
1976	7.82	157.64	5.24
1977	5.16	136.11	5.20
1978	4.92	129.78	5.03
1979	4.69	123.59	4.86
1980	4.41	116.43	4.68
1981	4.15	109.48	4.50
1982	3.86	102.03	4.31
1983	3.71	97.96	4.26
1984	3.11	77.23	3.73
1985	2.62	56.85	3.65
1986	2.44	53.96	3.56
1987	1.47	14.48	4.99
1988	1.28	13.89	4.80

TABLE 2-8. MEDIUM HEAVY-DUTY GASOLINE TRUCK EMISSION FACTORS FOR 1988

Model Year	HC	(gm/mile) CO	NOx
1967	26.28	345.81	8.84
1968	26.55	349.39	8.93
1969	15.97	325.89	9.40
1970	15.94	324.27	9.43
1971	15.83	320.95	9.42
1972	15.69	316.88	9.39
1973	15.67	315.31	9.43
1974	14.30	290.61	9.46
1975	14.26	288.57	9.49
1976	13.88	279.80	9.31
1977	9.04	238.44	9.11
1978	8.65	228.06	8.84
1979	8.26	217.92	8.57
1980	7.81	206.01	8.28
1981	7.36	194.43	7.99
1982	6.89	181.91	7.69
1983	6.61	174.64	7.59
1984	5.55	137.69	6.64
1985	4.67	101.34	6.51
1986	4.35	96.19	6.35
1987	4.03	91.07	6.20
1988	3.68	85.49	6.03

The estimated emission factors are comparable to the limited data available from chassis emissions tests of light and medium heavy-duty vehicles. Table 2-9 summarizes the emissions measured by Black and co-workers (1984) and Braddock and Perry (1986), testing various HDGTs on a chassis dynamometer. The calculated emission factors appear to underestimate the factors developed from test data for HC and NO_x. The calculated emission factors appear to overestimate the factors developed from test data for CO. The difference in NO_x emissions are not surprising, as the trucks tested were Federal, not California, vehicles. The calculated factors appear reasonable when compared to the limited available test data.

2.2 Expected I/M Failure Rates and Emission Reductions due to Repair

Estimates of HDGV failure rates and of the reduction in emissions per vehicle due to repair were based on several sources. For older trucks, these estimates were based on a previous Radian Corporation study which investigated the feasibility of an I/M program for HDGTs for the State of New York. The newest truck used in this study was a 1978 model vehicle, however, so the study results are not representative of subsequent, emission-controlled models. For newer model trucks, data for light-duty vehicles with comparable emissions control technology were used to estimate the emissions reduction due to repairs, while current data from the existing HDGT I/M program in Anchorage, Alaska were used to estimate failure rates. Failure rate data from the Portland HDGT I/M program were also studied.

New York Heavy-Duty Gasoline Truck I/M Study

The New York heavy-duty gasoline truck I/M study looked at the expected fleet impact on emissions of HC and CO. NOx was not recorded in the results of the study. 181 HDGTs from various fleets throughout the city were donated to be used for the study. It is expected that the emission reductions found in this study would be the maximum that could be expected from an I/M program. This is due to the fact that the individuals performing repairs were

TABLE 2-9. HEAVY-DUTY GASOLINE TRUCK EMISSION TEST DATA
HEAVY-DUTY TRANSIENT CYCLE

Make	Engine Type	Odom	Class	IW (lb)	Dyno Hp	HC (gm/mi)	CO (gm/mi)	NOx (gm/mi)	Fuel Econ. (mpg)
79 Ford F350	330 in^3 V-8	38,061	2B	7,080	41.0	12.86	80.30	6.66	9.66
78 Ford F350	330 in^3 V-8	54,415	2B	7,080	41.0	22.54	69.52	10.90	8.77
82 Plymouth Van	360 in^3 V-8	47,386	2B	6,032	35.5	4.29	82.70	3.67	9.49
83 Plymouth Van	360 in^3 V-8	23,561	2B	6,032	35.5	4.11	44.09	4.99	9.29
76 Ford Van	351 in^3 V-8	91,000	2B	6,380	47.5	10.0	101.1	8.7	6.9
72 Ford Van	330 in^3 V-8	37,000	5	12,830	67.5	33.99	370.75	5.91	5.35
79 Ford Van**	370 in^3 V-8	51,000*	5	14,560	66.4	22.7	147.6	9.5	4.7
79 Ford Stake-Bed**	370 in^3 V-8	51,000*	5	14,560	49.1	20.4	142.4	9.4	4.6
73 IH Stake-Bed	345 in^3 V-8	105,000	6	15,047	55.4	13.9	233.1	9.4	4.4
80 GM Van 1979	366 in^3 V-8	73,000*	6	15,798	55.4	26.3	113.7	8.3	4.8
75 GM Stake-Bed	350 in^3 V-8	35,000	6	16,378	50.4	31.4	237.4	10.2	5.1

* Less than 10,000 miles on the engine.
** Same vehicle, different dynamometer road load simulations.

experts in emission control repair. In addition, since the vehicles used for the study received free repairs and tune-ups, the fleet owners were most inclined to submit vehicles which would require some repair and/or tune-up.

The test procedure consisted of performing idle and 2500 RPM emission tests before and after the vehicle was repaired. Chassis dynamometer emission tests were also performed before and after repair. Table 2-10 lists the idle and 2500 RPM emission standards used with the New York study.

The reduction in in-use emissions, as determined by the New York study, was predicted from the results of emission tests of the vehicles while driving various cycles on a chassis dynamometer. All of the vehicles were tested using a cycle known as the New York Quick, while two-thirds of the vehicles were tested on a cycle known as the C39 or C39H. Although the New York Quick is a brief test, its results correlate quite well with the results from the C39. A detailed analysis correlating the results from the New York Quick Cycle to the C39 cycle was performed by Radian. A discussion of the correlation can be found in <u>An Assessment of Emission Reduction Strategies for Heavy-Duty Gasoline-Powered Trucks</u>. The C39 test is considered to be representative of urban driving. Although the cycle is not directly comparable to the current heavy-duty engine certification test, relative effects from this cycle are comparable to in-use driving.

The reduction in emissions measured on each test due to the I/M program is shown in Tables 2-11 and 2-12. In summarizing the data, the emission reductions have been quantified by model year and gross vehicle weight. The emission reductions are summarized for the two different tests, NY Quick and C39. The emission reductions are also calculated for repaired vehicles alone, and for the entire vehicle sample (including those which passed the inspection). The reductions are summarized by the percent difference of the average emissions, average percent difference in emissions, and the average difference in grams per mile.

TABLE 2-10. CUTPOINTS USED FOR HEAVY DUTY TRUCKS IN NEW YORK STUDY

Model Year	HC	CO (low idle)	CO (high idle)
Pre-70	1200 ppm	8.5%	3%
70-73	700 ppm	6.0%	3%
74-78	500 ppm	4.0%	3%
79-82	300 ppm	3.0%	3%
83	250 ppm	1.5%	3%

TABLE 2-11. NEW YORK HEAVY DUTY GASOLINE TRUCK I/M STUDY
HC EMISSION REDUCTIONS

	NYQ				C39			
	N	PD of Ave	Ave PD	Ave D (gpm)	N	PD of Ave	Ave PD	Ave D (gpm)
All Model Years								
I/M (42%)								
Repaired Veh's	68	45	32	10.2	46	44	34	19.9
Fleet	163	25	13	4.3	116	25	14	8.3
Pre-70								
I/M (46%)								
Repaired Veh's	15	43	32	11.0	11	20	18	6.1
Fleet	32	25	15	5.1	22	9	8	2.8
70-73								
I/M (40%)								
Repaired Veh's	44	43	32	9.5	31	46	32	22.6
Fleet	109	24	13	3.8	84	27	13	9.0
74-78								
I/M (41%)								
Repaired Veh's	9	61	34	12.3	4	64	27	37.1
Fleet	22	33	14	4.9	10	33	11	12.8
GVW: 14,000 and Less								
I/M (35%)								
Repaired Veh's	16	46	35	9.8	6	40	63	21.2
Fleet	46	28	12	3.4	21	27	22	7.4
GVW: 14,001 - 26,000								
I/M (43%)								
Repaired Veh's	29	34	30	6.0	19	23	21	7.5
Fleet	67	15	13	2.6	47	10	9	3.2
GVW: 26,000+								
I/M (46%)								
Repaired Veh's	23	54	34	15.7	21	57	38	30.8
Fleet	50	37	16	7.2	48	39	17	14.2

PD of Ave = % Difference of Average Emissions; Ave PD = Average % Difference;
D = Difference
(%) I/M Failure Rate

TABLE 2-12. NEW YORK HEAVY-DUTY GASOLINE TRUCK I/M STUDY
CO EMISSION REDUCTIONS

	NYQ				C39			
	N	PD of Ave	Ave PD	Ave D (gpm)	N	PD of Ave	Ave PD	Ave D (gpm)
All Model Years								
I/M (42%)								
Repaired Veh's	68	37	33	84	46	43	33	184
Fleet	163	21	14	35	116	25	14	77
Pre-70								
I/M (46%)								
Repaired Veh's	15	43	34	142	11	53	44	290
Fleet	32	26	16	65	22	31	20	133
70-73								
I/M (40%)								
Repaired Veh's	44	35	35	70	31	39	30	161
Fleet	109	19	14	28	84	23	12	64
74-78								
I/M (41%)								
Repaired Veh's	9	31	25	51	4	29	27	68
Fleet	22	15	10	21	10	12	11	28
GVW: 14,000 and Less								
I/M (35%)								
Repaired Veh's	16	22	20	31	6	(5)	(25)	(9)
Fleet	46	10	7	11	21	(1.6)	(9)	(3)
GVW: 14,001 - 26,000								
I/M (43%)								
Repaired Veh's	29	40	35	96	19	48	42	204
Fleet	67	21	15	41	47	28	18	88
GVW: 26,000+								
I/M (46%)								
Repaired Veh's	23	54	41	104	21	45	42	221
Fleet	50	25	19	48	48	29	19	102

PD of Ave = % Difference of Average Emissions; Ave PD = Average % Difference;
D = Difference (%) I/M Failure Rate

The percent difference of average emissions and the average percent difference were both calculated since one tends to overestimate the emission reductions, while the other tends to underestimate the emission reductions. For a large sample, the percent difference in the average emissions is most likely the best method to determine the improvement. However, for a small sample this method could bias the results. This is because a vehicle with a large mass reduction in emissions can overshadow the results from a number of vehicles which had a small reduction in mass emissions. The average percent difference has the possibility of biasing the emission reductions on the low side. This is because a vehicle which is very dirty can at the very most improve by only 100 percent. On the other hand, a relatively clean vehicle can worsen and produce increases in emissions of several hundred percent, thereby biasing the emission reductions on the low side. Since the sample size of the New York data was fairly small the average percent difference was used to predict the emission reductions. This would tend to bias the estimated reduction toward the low end.

The New York data were used to predict the percent emission reductions for HC and CO for 1974 and earlier model California HDGTs. The vehicles used for the New York study were not equipped with significant emission control devices (i.e. EGR valves, Air Injection Systems, etc.). HDGTs certified to Federal standards did not start using emission control devices until the 1979 model year. In California, HDGTs started using these devices to meet the HDGT engine standards in the 1975 model year. For model years after this the ARB I/M evaluation data was used to determine the percent emission reductions that could be expected due to an I/M program.

The emission reductions used for the pre-1975 California HDGTs were taken from the summary for the repaired vehicles only. The average emissions reduction due to repairs for all model years was 34% for HC and 33% for CO. The results of the C39 testing showed CO reductions to be quite dependent upon GVW, with the light heavy-duty gasoline trucks showing a minimal reduction in CO and the medium heavy-duty gasoline trucks showing a larger improvement. The

CO emission reduction for the light HDGT fleet was estimated to be 20%, and the medium HDGT fleet was estimated to be 37%. These estimates were obtained from the New York Quick test results. No GVW trend was observed for the HC emission reductions. Tables 2-13 and 2-14 show the estimated emission reductions by model year due to repair for the light HDGT fleet and the medium HDGT fleet respectively.

The New York study did not evaluate any reductions in NOx emissions from the HDGT fleet. None of the vehicles tested had any EGR systems or other specific control systems designed to reduce NOx emissions. Therefore, it is quite likely that the repairs would not have produced any significant reduction in the NOx emissions of the fleet. For these model years it is assumed that the benefit of repair to NOx emissions is zero.

In looking at the failure data of the New York fleet, a trend in the number of vehicles failed based on GVW is observed. In general, it is observed that the greater the GVW the higher the failure rate. This is possibly due to the increased loading placed on engines operating in a heavier vehicle. Therefore, a higher failure rate (42%) is used for the medium HDGTs while a lower failure rate (35%) is used for the light HDGTs. The I/M failure rate for light HDGTs is the same as the failure rate for vehicles in the New York study with GVWs less than 14,000 lb. The I/M failure rate for medium HDGTs was conservatively estimated to be one percent less than the I/M failure rate for vehicles with GVWs of 14,000 to 26,000 lb in the New York study. In addition, data from the Anchorage HDGT I/M program were used to verify the I/M failure rates observed in the New York study. The estimated failure rates for the medium and light HDGT fleets can be found in Table 2-15.

Improvement in Fuel Economy

An additional benefit of the I/M program is an increase in the fleet average fuel economy. As part of the New York evaluation, the fuel economy of each repaired vehicle was measured during the chassis dynamometer tests. The

TABLE 2-13. EMISSION REDUCTION DUE TO REPAIR
LIGHT HEAVY-DUTY GASOLINE TRUCKS
1988

Model Year	HC	(%) CO	NOx
1967	34	20	0
1968	34	20	0
1969	34	20	0
1970	34	20	0
1971	34	20	0
1972	34	20	0
1973	34	20	0
1974	34	20	0
1975	37	16	5
1976	37	16	5
1977	37	16	5
1978	37	16	5
1979	37	16	5
1980	37	16	5
1981	37	16	5
1982	37	16	5
1983	37	16	5
1984	37	16	5
1985	37	16	5
1986	37	16	5
1987	23	20	10
1988	23	20	10

Sources: Model years 1967 through 1974 - Radian Corporation (1981).

Model Years 1975 through 1986 - Pre-1975 light-duty vehicles studied in the ARB I/M Evaluation Program. Sierra Research, (1986).

Model years 1987 through 1988 - 1975 through 1979 light-duty vehicles studied in the ARB I/M Evaluation Program. Sierra Research (1986).

TABLE 2-14. EMISSION REDUCTION DUE TO REPAIR
MEDIUM HEAVY-DUTY GASOLINE TRUCKS
1988

Model Year	HC	(%) CO	NOx
1967	34	37	0
1968	34	37	0
1969	34	37	0
1970	34	37	0
1971	34	37	0
1972	34	37	0
1973	34	37	0
1974	34	37	0
1975	37	20	5
1976	37	20	5
1977	37	20	5
1978	37	20	5
1979	37	20	5
1980	37	20	5
1981	37	20	5
1982	37	20	5
1983	37	20	5
1984	37	20	5
1985	37	20	5
1986	37	20	5
1987	37	20	5
1988	37	20	5

Sources: Model Years 1967 through 1974 - Radian Corporation (1981).

Model years 1975 through 1988 - Pre-1975 light-duty vehicles studied in the ARB I/M Evaluation Program. Sierra Research (1986).

TABLE 2-15. I/M FAILURE RATES
1988

Model Year	LIGHT HEAVY-DUTY GASOLINE TRUCKS (%)	MEDIUM HEAVY-DUTY GASOLINE TRUCKS (%)
1967	35	42
1968	35	42
1969	35	42
1970	35	42
1971	35	42
1972	35	42
1973	30	35
1974	30	35
1975	30	35
1976	30	35
1977	30	35
1978	25	30
1979	25	30
1980	25	30
1981	25	30
1982	18	23
1983	16	21
1984	14	19
1985	12	17
1986	10	15
1987	9	13
1988	8	12

Sources: Model years 1967 through 1972 - Radian Corporation (1981).

Model years 1973 through 1988 - Anchorage, Alaska data provided by Sierra Research.

result of the New York study was an improvement in fleet composite fuel economy of 1.9 percent. This corresponds to a 4.7 percent increase in fuel economy for the repaired vehicles only. This compares favorably with other reports of fuel economy improvements of 2 to 5 percent for heavy-duty gasoline trucks. (Householder and Jasper, 1984)

Summary of the ARB I/M Evaluation Program

ARB measured the effectiveness of the current Smog Check Program in California by sending undercover vehicles to various Smog Check stations throughout the South Coast Air Basin (Sierra Research, 1986). These undercover vehicles were known to be vehicles that would fail the Smog Check, since they had failed a screening check performed by the ARB. Thirty-two percent of these vehicles passed inspection at the Smog Check stations. The vehicles that failed were repaired at the Smog Check station and then were retested at the El Monte Laboratory. Using this information, estimates of emission reductions due to repair can be made for technology specific vehicle classes. From this study, estimates of emission improvements achieved by I/M can be forecast for HDGTs using similar emission control technology.

One concern in using light-duty emissions data as a surrogate for heavy-duty data lies in the possibility of different maintenance practices between the two classes. There is a widespread belief that--since HDGTs are used primarily for business purposes--these trucks would be in a better state of repair than the light-duty vehicle fleet. In another study currently underway to determine the feasibility of a diesel I/M program, a large percentage of the California diesel fleet was found to be poorly maintained (Weaver, 1986). Since the diesel fleet and the HDGT fleet are used for similar purposes, it is likely that both fleets are in a similar state of maintenance.

Another concern when using light-duty vehicle fleets as a surrogate for heavy-duty gasoline truck fleets, is the difference in age between the fleets. Since the surrogate fleet is older than the HDGT fleet, there is a concern that the failure rates for the truck fleet should be less than the light-duty fleet. This difference does exist, and could possibly lead to an overestimate of failure rates for the HDGT fleet. For this reason, failure rate data from the Anchorage, Alaska HDGT I/M program were used to estimate failure rates in California; the light-duty surrogate data were used only to estimate the percentage reduction in emissions in repaired vehicles.

Another factor to consider in comparing HDGT emissions data to LDV data is the difference in rates of mileage accumulation. The current data shows that the average LDV travels approximately 20% fewer miles per year than the average HDGT (California Air Resources Board, 1986). Also, the HDGT fleet spends most of its operating time in the relatively strenuous urban environment. These characteristics of the truck's operation would tend to offset the effects of the age differences between LDVs and HDGTs with comparable emissions control technologies.

Surrogate Fleet Emission Control Technology

The technology level of the heavy-duty gasoline truck fleet needs to be determined in order to select surrogate LDV fleets. The technology level of the California HDGT fleet is listed below:

Model Year	California Heavy-Duty Gasoline Trucks
pre-1975	No specific emission control devices
1975-1986	EGR and Air Injection found on most engines
1987 and later	Light HDGTs: EGR, Air Injection, and some use of oxidizing catalytic converters Medium HDGTs: EGR and Air Injection, no use of catalytic converters

The surrogate light-duty vehicle fleet needs to have emission control technologies similar to the HDGT fleet. As can be seen, the surrogate fleet data can be used for both the light and medium HDGT fleets until the 1987 model year. After that date, the technology used to control emissions in the two cateogories begins to differ. Therefore, two sets of surrogate data are required for 1987 and later model trucks.

The California Highway Patrol performed random roadside inspections of light-duty vehicles in 1985 and 1986 (Sierra Research, 1986). These under-hood inspections were used to determine the emissions status of the light-duty vehicle fleet. The results of these inspections show the percentage of in-use vehicles that should have the various emission control devices. These data are shown in Table 2-16. The information in this table was used to determine which LDV classes could be used as surrogates for the HDGTs.

From the data in Table 2-16, it appears that most vehicles between model years 1975 and 1979 (84% from the 1986 survey) used catalytic converters. The majority of catalytic converters used in this time frame were oxidation catalysts, since the usage of O2 sensors for this technology group is only 4.3%. This technology group can be used as a surrogate for the 1987 and later model light HDGTs. For the light HDGTs built from 1975 through 1986, and the medium HDGTs built after 1974 another surrogate group will need to be used.

For the 1975 through 1987 light HDGTs and the 1975 and newer medium HDGTs, the noncatalyst 1975 through 1979 LDV group was studied for use as a surrogate. The noncatalyst vehicle group in the 1975 to 1979 model year range was quite small, less than 10 vehicles. These vehicles did not show any net benefit due to repair. The noncatalyst vehicles which failed the tailpipe test did show reductions in HC and NOx emissions due to repair; no CO benefit due to repair was noted. However, the repair of vehicles failing the visual/functional check resulted in increased emissions from these vehicles. The total repair benefit was zero due to the increase in emissions from the vehicles failing only the visual/functional check. Due to the small size of this group and overall zero emission reduction due to repair, this group was not used as a surrogate.

TABLE 2-16. EMISSIONS CONTROL TECHNOLOGY USAGE BY MODEL YEAR FOR LIGHT-DUTY VEHICLES - RANDOM ROADSIDE SURVEY DATA

Technology	Pre-75	75-79	80+
AIR INJECTION	29.4%	77.0%	77.2%
CATALYTIC CONVERTER	--	84.0%	98.9%
SPARK	98.3%	98.4%	75.1%
EVAP	66.2%	97.9%	99.6%
EGR	27.7%	87.1%	90.9%
LEAD FILL PIPE RESTRICTOR	--	85.5%	99.4%
O2S	0%	4.26%	70.7%
PCV	85.1%	99.8%	99.6%
TAC	--	91.3%	88.4%

Reference: Sierra Research, (1986)

The pre-75 LDV class was used as the surrogate for the 1975 and newer medium HDGTs and the 1975 through 1986 light HDGTs. The majority of the pre-75 LDVs surveyed in the roadside inspections did not have any emission control technology; however, a sizeable percentage did have EGR and AIR, 35% and 29%, respectively.

Emission Reductions Due to Repair

For the 1987 and later model light HDGTs the estimated emission benefits of repair can be found in Table 2-17. These data are for 1975 through 1979 model year LDVs that have an oxidizing catalyst and air injection system. They are segregated into two categories: vehicles which failed the tailpipe test and those which failed the visual/functional check. Percentage improvements due to repair can be calculated from the data. The percent differences in emissions for both failures were aggregated to determine the overall emission reduction due to repair. These data are also shown on Table 2-13.

Finally, emission improvements due to repair need to be determined for the 1975 and newer light and medium heavy-duty gasoline trucks. These vehicles had emission control technology similar to the pre-75 light-duty vehicles. Regressions linking FTP HC and CO to idle HC and CO for the before and after repair samples were developed with data from the ARB I/M Evaluation Program. These regression equations were combined with TAS data showing the reductions in idle HC and CO to calculate emission benefits for the pre-1975 vehicles (Sierra Research, 1986).

As has been shown elsewhere, reductions in idle emissions cannot be used to accurately predict reductions of in-use emissions. Unfortunately, the authors are not aware of any other data base which could be used to more accurately predict the emission reductions from HDGVs. Therefore, for lack of a better data base, the regressions will be used as an estimate of the reduction in emissions for the HDGV fleet that uses EGR and AIR.

TABLE 2-17. BENEFITS DUE TO EMISSION REPAIR: 1975 - 1979 LIGHT-DUTY VEHICLES

	Tailpipe			Visual/Functional		
	HC (gm/mi)	CO (gm/mi)	NOx (gm/mi)	HC (gm/mi)	CO (gm/mi)	NOx (gm/mi)
1975-1976		N-45			N-17	
F-Sample Cars (CARB/OXD/AIR)						
Before repair	6.08	69.04	3.01	2.78	41.60	2.61
After repair	3.33	45.99	2.64	1.87	29.54	2.46
Difference	2.75	23.05	0.37	0.91	12.06	0.15
Percent Difference	45.2%	33.4%	12.3%	32.7%	29.0%	5.7%
1977-1979		N-37			N-28	
F-Sample Cars (CARB/OXD/AIR)						
Before repair	3.20	48.39	2.44	1.43	14.80	2.94
After repair	3.13	38.71	2.27	1.33	15.24	2.47
Difference	0.07	9.68	0.17	0.10	-0.49	0.47
Percent Difference	2.2%	20.0%	7.0%	7.0%	-3.3%	16.0%
Weighted Percent Difference	25.8%	27.4%	9.9%	16.7%	8.9%	12.1%

	HC	CO	NOx
Weighted Average of Improvements (assumed to apply to 1987+ LHDV)	23%	20%	10%

Reference: Sierra Research (1986)

With the regression equations and the TAS data describing the idle emission reductions, technology-specific reductions due to repair can be estimated. Table 2-18 lists the benefits of repair for the pre-75 light-duty vehicles with AIR. The reduction due to repair was calculated using the following equations:

$$HC = 1.691 + (.917 \times \Delta \text{Idle HC} \times 10^{-2})$$

$$CO = 6.796 \times \Delta \text{Idle CO}$$

The change in idle HC and CO was determined from South Coast Air Basin TAS data. The reduction in idle HC was 404 ppm while the reduction in idle CO was 1.86 %. This data was for vehicles with AIR. A regression equation was not available to calculate the NOx reduction. Therefore, the 1971-1974 aggregate emission reduction due to repair from the California ARB I/M Evaluation Program was used for the NOx value (Sierra Research, 1986). The resulting estimates are also shown in Tables 2-13 and 2-14.

Based on the New York study, CO emission reductions due to repair were significantly greater for medium HDGTs than for light HDGTs. This difference is thought to be caused by the increased load placed on the engine in the medium HDGTs compared to the light HDGT. This difference would also be expected with the newer model trucks since the operating characteristics (i.e., engine load) is the same. For pre-1975 model HDGTs, the CO reduction for medium HDGTs was 85% greater than light HDGTs; for 1975 and newer medium HDGTs the CO reduction is conservatively estimated to be 25% greater than the CO reduction for light HDGTs.

Expected I/M Failure Rates

The March, 1986 TAS failure rates for 1975 through 1979 model year LDVs can be found in Table 2-19. The March, 1986 TAS data was compared to failure rate data from the Anchorage, Alaska I/M program. Seventy-eight

TABLE 2-18. BENEFITS OF REPAIR: PRE-1975 LIGHT-DUTY VEHICLES

	N=61		
1971-1974	HC (grams/mile)	CO (grams/mile)	NO (grams/mile)
Before repair	14.71	78.22	3.10
Reduction due to repair	5.40	12.64	.15
% Reduction	37%	16%	5%

CARB I/M Undercover Vehicle Test Data

Reference: Sierra Research (1986).

TABLE 2-19. I/M FAILURE RATES REPORTED FROM 3/86 TAS DATA 1975 CARS

Model Year	Tailpipe (%)	Visual/Functional (%)	Total (%)
1979	25.2	8.0	29.6
1978	31.3	9.4	36.1
1977	31.3	12.2	39.9
1976	38.3	12.6	43.4
1975	45.3	14.6	50.5

Reference: Sierra Research (1986).

percent of all the HDGTs tested in the Anchorage I/M program passed on the initial test. For '75 through '78 model trucks 35.2% of the trucks fail the initial test; for pre-75 model HDGTs 33.1% of the HDGTs fail the initial test, while 13.6% of the '79 and newer model HDGTs fail initially.

Based on the Anchorage data, the LDV failure rate in the California program seems quite high. Therefore, a failure rate distribution has been developed for light and medium HDGTs, based on the Anchorage data. The Anchorage failure rate data were segregated into three model year groups. The groups consisted of pre-75 HDGTs, 1975 through 1978 HDGTs, and 1979 and newer HDGTs. These age groupings and failure rates were used as the basis for the failure rates used in this study. The 1979 and newer model trucks in the Anchorage fleet correspond in age to the 1981 and newer model trucks in this study. The average failure rate for light and medium HDGTs in this age group was set equal to the Anchorage data for this group plus two percent. Based on previous I/M programs, the failure rate is expected to be slightly higher in the initial year of the program. For the 1995 analysis, the failure rate was decreased by approximately two percent to correspond to the failure rate reduction that is observed as the program continues. In addition, the failure rate for a given model year is expected to increase each year as the vehicles age. The same methodology was used for all model year groupings. The resulting failure rate estimates are given in Table 2-15.

The Anchorage HDGT I/M program only uses CO emission standards. Hydrocarbon emissions are also measured but are not used as pass/fail criteria. The CO cutpoints vary from three percent to five percent based on model year. If the CO concentration in the exhaust is greater than the cutpoint at idle or 2500 RPM, the vehicle fails the "Smog Check." All heavy-duty gasoline vehicles with a rated GVW greater than 8500 lb are tested.

Failure rates from the Portland, Oregon HDGV I/M program for the 1983 calendar year were also reviewed. Table 2-20 summarizes the data from the Portland program. The model year groupings through 1973 correspond to

TABLE 2-20. PORTLAND, OREGON HEAVY-DUTY GASOLINE VEHICLE TEST SUMMARY 1983

EMISSION INSPECTION TESTS	13284
OVERALL PERCENTAGE PASS	65%
OVERALL PERCENTAGE FAIL	35%
Pre-1970 Trucks	
Total Tests	2683
Pass I/M Test	64.2%
Fail I/M Test	35.8%
1970-1973 Trucks	
Total Tests	2256
Pass I/M Test	62.3%
Fail I/M Test	37.7%
1974-1978 Trucks	
Total Tests	5092
Pass I/M Test	62.0%
Fail I/M Test	38.0%
1979 and Later Trucks	
Total Tests	3253
Pass I/M Test	72.5%
Fail I/M Test	27.5%

Reference: Householder and Jasper, (1984) California vehicles that would have no specific emission control devices. The later model year groupings correspond to vehicles which would most likely have EGR valves and AIR pumps. The failure rates for this program are significantly higher than the Anchorage program. While Anchorage had an overall failure rate of 22 percent, Portland had an overall failure rate of 35 percent. The aggregate failure rate for all model year 1978 and older trucks (trucks at least five years old) is in the 37 percent range. The failure rate for trucks four years old or newer is 27.5 percent.

The failure rate data used in the model were developed from the Anchorage data. These data are the most conservative of the three sources that were reviewed. The model will thus underpredict the emission reductions if the HDGV failure rate is similar to the Portland failure rate or the surrogate California LDV failure rate.

Differences Between Heavy-Duty Vehicle I/M Data Sources

Four separate sources of data were reviewed for the development of cutpoints and failure rates. Data were obtained from two HDGT I/M programs, Portland and Anchorage, a test program performed in New York, and the California light-duty vehicle I/M program.

The California and New York data are not directly applicable to the current California HDGT fleet. The California data are from passenger cars and light-duty trucks. Differences in vehicle age between the light-duty and heavy-duty vehicles could lead to overestimates of failure rates. Failure rates from the light-duty fleet were not used to estimate heavy-duty vehicle failure rates. Light-duty vehicle emission improvements due to repair were used for heavy-duty vehicles with similar emission control technology.

The New York study tested heavy-duty vehicles which were submitted by their owners. The vehicles did not have any emission control devices other than a PCV valve The I/M failure rates and emission reduction due to repair from this study are applicable to older vehicles in California which do not have any emission control devices. Emission cutpoints and failure rates from this study can be found in Tables 2-10, 2-11, and 2-12.

Data from the heavy-duty vehicle I/M programs which are operating in Anchorage, Alaska, and Portland, Oregon, were studied to determine failure rates for late model California heavy-duty vehicles. Significant differences exist in the failure rates between these two programs. As would be expected, the operation of these two programs is different. The Portland program is a centralized I/M program while the Anchorage program is decentralized. The Portland program does not have a cost limit or any method of obtaining a waiver from having the vehicle completely repaired. Anchorage has a cost ceiling for both defects not associated with tampering and tampering defects.

In addition to these differences, there are differences in the cutpoints between the two programs. The Anchorage program does not have a cutpoint for HC. As long as the vehicle meets the CO standard listed in Table 4-2, it will pass the tailpipe portion of the I/M test. The CO standard is measured at 2,500 RPM and idle. The high and low speed CO standards are the same.

The Portland program has cutpoints for both HC and CO. Table 4-1 and 4-2 list the cutpoints used for the Portland program. Portland has an idle CO and 2,500 RPM CO standard. The idle CO standard is the same for the Portland and Anchorage I/M programs. The Portland 2,500 RPM CO standard is 3 percent for all 1970 and newer model trucks. This is more stringent than the Anchorage standard for 1970 through 1978 model year trucks.

The variation in failure rates between the Anchorage and Portland programs can be attributed to the differences in the cutpoints. In general, the Portland cutpoints are more stringent than the Anchorage cutpoints.

2.3 Estimation of Daily Vehicle Miles Travelled by the Heavy-Duty Gas Truck Fleet

The next step in determining the potential emission reductions from a HDGT I/M program was to estimate the annual vehicle miles travelled (VMT) by the fleet. For this study two sets of data would be required, one describing the daily VMT for the light HDGT fleet and the other detailing the VMT of the medium HDGT fleet. Estimates of the future VMT of the two fleets were also required.

The DVMT of the HDGT fleet for 1983 was used as the basis for the VMT calculation. The data included estimates of the fraction of VMT by light and medium heavy-duty trucks, in addition to estimating DVMT by fuel usage (Pacific Environmental Services, 1985). Table 2-21 lists the estimated DVMT by air basin for California in 1983.

To calculate the current DVMT of the fleet, estimates of DVMT growth since 1983 were developed. These calculations were based on data supplied by CalTrans. CalTrans estimates of the number of vehicles by class in addition to the VMT by age distribution were used to calculate the DVMT growth. The age distributions of the the medium and light HDGT fleets can be found in Tables 2-22 and 2-23. The age distribution of VMT can be found in Table 2-24. Finally, the estimated VMT growth of the light and medium HDGT fleets can be found in Tables 2-25 and 2-26, respectively.

2.4 Estimating the Emission Reduction due to the Implementation of a Heavy-Duty Gasoline Truck I/M Program

The emission reduction due to the implementation of an I/M program was estimated, using the projected fleet size and age structure for 1988. A similar estimate was made for 1995. The spreadsheets used to calculate the 1995 reduction can be found in Appendix A. Separate emission reduction estimates were prepared for I/M of the light and medium heavy-duty fleets. The methodology for doing this is summarized in Section 2.2.

TABLE 2-21. ANNUAL AVERAGE DVMT BY AIR BASIN
RURAL/URBAN, GASOLINE, CALIFORNIA BASED

AIR BASIN	LIGHT	MEDIUM
NORTH COAST	110,505	141,926
SAN FRANCISCO	1,097,039	1,187,209
N. CENTRAL COAST	155,642	165,679
S. CENTRAL COAST	308,002	328,897
SOUTH COAST	2,995,550	3,064,339
SAN DIEGO	520,305	521,762
NORTHEAST PLATEAU	71,621	105,258
SACRAMENTO VALLEY	460,071	505,523
SAN JOAQUIN VALLEY	688,676	752,542
GREAT BASIN VALLEY	27,015	30,283
SOUTHEAST DESERT	554,624	610,624
MOUNTAIN COUNTIES	196,336	165,124
LAKE COUNTY	13,537	14,011
LAKE TAHOE	27,877	8,291
TOTALS	7,226,800	7,601,468

TABLE 2-22. NUMBER OF GASOLINE VEHICLES IN CALIFORNIA BY CLASS (000s)

LIGHT HEAVY-DUTY

YEAR	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995
0	11.108	10.799	12.262	13.233	13.769	14.195	14.702	15.169	15.498	15.696	15.639
1	13.662	17.502	15.954	16.583	17.198	17.677	18.169	18.750	19.218	19.732	20.016
2	9.760	14.286	17.334	15.339	15.750	16.271	16.687	17.122	17.662	18.173	18.715
3	9.930	9.586	14.095	17.216	15.283	15.703	16.226	16.635	17.095	17.634	18.116
4	11.563	9.698	9.405	13.920	17.056	15.151	15.571	16.084	16.515	16.972	17.480
5	12.219	11.219	9.452	9.227	13.699	16.797	14.925	15.333	15.862	16.288	16.712
6	26.336	11.769	10.854	9.206	9.015	13.394	16.426	14.590	15.012	15.531	15.923
7	25.006	25.167	11.297	10.488	8.923	8.744	12.995	15.931	14.172	14.583	15.063
8	28.002	23.693	23.951	10.823	10.080	8.582	8.411	12.496	15.343	13.649	14.023
9	15.411	26.293	22.346	22.740	10.308	9.607	8.181	8.016	11.927	14.645	13.008
10	11.495	14.332	24.560	21.013	21.451	9.731	9.070	7.721	7.577	11.274	13.822
11	7.824	10.583	13.254	22.864	19.623	20.046	9.095	8.475	7.226	7.091	10.535
12	11.181	7.126	9.683	12.207	21.125	18.143	18.538	8.408	7.847	6.691	6.555
13	9.543	10.072	6.448	8.819	11.153	19.315	16.592	16.947	7.699	7.185	6.117
14	6.499	8.497	9.007	5.805	7.965	10.080	17.460	14.993	15.338	6.968	6.493
15	6.480	5.717	7.508	8.012	5.180	7.112	9.003	15.588	13.407	13.716	6.221
16	6.082	5.629	4.988	6.595	7.060	4.568	6.272	7.937	13.765	11.839	12.093
17	3.704	5.215	4.848	4.325	5.736	6.144	3.976	5.458	6.918	11.997	10.302
18	1.706	3.217	4.549	4.257	3.810	5.056	5.418	3.505	4.819	6.107	10.575
19	1.887	1.482	2.807	3.995	3.751	3.359	4.458	4.776	3.094	4.254	5.383
20	9.094	9.537	9.612	10.906	13.127	14.879	16.081	18.105	20.199	20.564	21.876
TOTALS	238.492	241.419	244.213	247.571	251.061	254.556	258.256	262.039	266.192	270.589	274.667

TABLE 2-23. NUMBER OF GASOLINE VEHICLES IN CALIFORNIA BY CLASS (000s)

	MEDIUM HEAVY-DUTY										
YEAR	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995
0	6.264	4.540	5.684	6.504	6.993	7.212	7.500	7.711	7.837	7.912	7.890
1	5.227	9.207	6.935	7.845	8.550	8.979	9.244	9.554	9.752	9.968	10.093
2	1.991	5.612	9.120	6.651	7.436	8.079	8.477	8.710	9.001	9.223	9.456
3	2.478	1.955	5.537	9.057	6.626	7.414	8.057	8.450	8.696	8.987	9.195
4	3.577	2.421	1.918	5.468	8.973	6.569	7.351	7.986	8.389	8.634	8.909
5	5.487	3.471	2.359	1.882	5.381	8.838	6.470	7.239	7.876	8.273	8.502
6	9.785	5.286	3.358	2.298	1.839	5.261	8.642	6.326	7.087	7.712	8.089
7	8.807	9.351	5.073	3.245	2.227	1.783	5.104	8.381	6.144	6.885	7.479
8	8.227	8.344	8.900	4.861	3.119	2.142	1.716	4.909	8.073	5.917	6.621
9	6.666	7.725	7.871	8.450	4.630	2.972	2.042	1.635	4.685	7.704	5.640
10	8.546	6.199	7.216	7.401	7.970	4.370	2.806	1.927	1.545	4.429	7.272
11	8.596	7.867	5.732	6.717	6.911	7.448	4.084	2.623	1.804	1.446	4.139
12	9.874	7.830	7.198	5.280	6.206	6.390	6.888	3.776	2.428	1.670	1.337
13	8.861	8.894	7.085	6.556	4.824	5.675	5.844	6.297	3.457	2.224	1.526
14	5.863	7.890	7.954	6.378	5.921	4.360	5.130	5.280	5.700	3.129	2.009
15	7.560	5.158	6.971	7.075	5.691	5.287	3.894	4.580	4.722	5.096	2.794
16	8.511	6.567	4.500	6.124	6.235	5.018	4.663	3.433	4.044	4.169	4.493
17	5.884	7.298	5.655	3.901	5.326	5.426	4.368	4.058	2.992	3.525	3.628
18	3.104	5.111	6.366	4.967	3.437	4.695	4.785	3.851	3.583	2.642	3.107
19	5.581	2.696	4.458	5.591	4.376	3.030	4.140	4.217	3.400	3.162	2.329
20	26.906	28.215	27.996	27.596	29.237	29.632	28.799	29.035	29.285	28.917	28.277
TOTALS	157.795	151.637	147.886	143.847	141.908	140.58	140.004	139.978	140.5	141.624	142.785

TABLE 2-24. VMT DISTRIBUTIONS - FROM CALTRANS MVSTAFF MODEL ANNUAL VMT (000's)

VEHICLE AGE	LIGHT	MEDIUM
0	14.865	13.677
1	18.923	24.744
2	17.513	22.621
3	16.291	20.763
4	15.192	19.079
5	14.183	17.522
6	13.241	16.064
7	12.355	14.686
8	11.514	13.373
9	10.711	12.116
10	9.941	10.907
11	9.2	9.74
12	8.485	8.611
13	7.792	7.515
14	7.119	6.45
15	6.466	5.411
16	5.829	4.398
17	5.207	3.408
18	4.6	2.439
19	4.06	1.489
20	3.425	0.558

TABLE 2-25. ANNUAL VMT DISTRIBUTION BY MODEL YEAR (in 1000s)

	LIGHT HEAVY-DUTY										
YEAR	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995
0	165123	160521	182271	196707	204670	211008	218540	225481	230383	233326	232473
1	258533	331196	301907	313791	325440	334500	343816	354807	363657	373395	378759
2	170926	250198	303570	268639	275833	284956	292247	299857	309308	318260	327761
3	161768	156173	229620	280465	248974	255821	264331	271005	278491	287276	295129
4	175660	147338	142875	211469	259110	230179	236550	244341	250899	257836	265553
5	173301	159112	134052	130861	194299	238238	211677	217465	224973	231016	237033
6	348715	155840	143718	121891	119364	177352	217500	193187	198776	205645	210841
7	308949	310932	139574	129578	110245	108035	160548	196828	175097	180167	186103
8	322416	272798	275772	124616	116057	98812	96847	143876	176662	157159	161460
9	165072	281626	239345	243569	110413	102900	87625	85857	127746	156859	139325
10	114272	142476	244156	208887	213244	96734	90169	76759	75326	112080	137406
11	71978	97365	121935	210350	180532	184427	83676	77973	66478	65240	96921
12	94873	60467	82157	103577	179245	153944	157294	71343	66581	56770	55623
13	74360	78479	50241	68718	86907	150503	129284	132054	59987	55986	47660
14	46263	60489	64124	41326	56703	71761	124296	106737	109192	49604	46222
15	41900	36964	48547	51807	33493	45987	58211	100794	86688	88685	40225
16	35451	32812	29076	38441	41153	26624	36562	46266	80235	69007	70488
17	19288	27152	25243	22519	29866	31994	20702	28421	36020	62468	53643
18	7848	14799	20926	19584	17525	23259	24922	16121	22166	28093	48644
19	7660	6016	11395	16219	15228	13636	18101	19389	12561	17272	21856
20	31146	32663	32921	37353	44960	50961	55077	62008	69182	70431	74926
TOTAL	2795499	2815415	2823424	2840366	2863262	2891631	2927976	2970571	3020407	3076576	3128052
ESCAL.	1.0406	1.0481	1.0510	1.0573	1.0659	1.0764	1.0900	1.1058	1.1244	1.1453	1.1644
FROM 83 2686320											

TABLE 2-26. ANNUAL VMT DISTRIBUTION BY MODEL YEAR (in 1000s)

	MEDIUM HEAVY-DUTY										
YEAR	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995
0	85673	62094	77740	88955	95643	98639	102578	105463	107187	108212	107912
1	129337	227818	171600	194117	211561	222176	228734	236404	241303	246648	249741
2	45038	126949	206304	150452	168210	182755	191758	197029	203612	208633	213904
3	51451	40592	114965	188050	137576	153937	167287	175447	180555	186597	190916
4	68246	46190	36594	104324	171196	125330	140250	152365	160054	164728	169975
5	96143	60819	41334	32976	94286	154859	113367	126842	138003	144960	148972
6	157186	84914	53943	36915	29542	84513	138825	101621	113846	123886	129942
7	129340	137329	74502	47656	32706	26185	74957	123083	90231	101113	109837
8	110020	111584	119020	65006	41710	28645	22948	65648	107960	79128	88543
9	80765	93596	95365	102380	56097	36009	24741	19810	56763	93342	68334
10	93211	67612	78705	80723	86929	47664	30605	21018	16851	48307	79316
11	83725	76625	55830	65424	67313	72544	39778	25548	17571	14084	40314
12	85025	67424	61982	45466	53440	55024	59313	32515	20908	14380	11513
13	66590	66838	53244	49268	36252	42648	43918	47322	25979	16713	11468
14	37816	50891	51303	41138	38190	28122	33089	34056	36765	20182	12958
15	40907	27910	37720	38283	30794	28608	21070	24782	25551	27574	15118
16	37431	28882	19791	26933	27422	22069	20508	15098	17786	18335	19760
17	20053	24872	19272	13295	18151	18492	14886	13830	10197	12013	12364
18	7571	12466	15527	12115	8383	11451	11671	9393	8739	6444	7578
19	8310	4014	6638	8325	6516	4512	6164	6279	5063	4708	3468
20	15014	15744	15622	15399	16314	16535	16070	16202	16341	16136	15779
TOTAL	1448852	1435162	1406999	1407200	1428231	1460715	1502516	1549755	1601264	1656125	1707710
ESCAL.	0.9691	0.9600	0.9411	0.9413	0.9553	0.9771	1.0050	1.0366	1.0711	1.1078	1.1423
FROM 83 1495000											

The VMT data developed in Section 2.3 are based on calendar years, while the emission factor data are given by model year. In order to combine the two sets of data the emission factors for each model year must be weighted and aggregated into a calendar year composite. The I/M failure rate data and the improvement due to repair were combined to calculate the average percentage reduction in emissions for the light and medium HDGT fleets, respectively. The emission factor data were then multiplied by the fleet emission reduction to determine the average reduction in grams/mile for the fleet. Finally, the grams/mile reduction was multiplied by total VMT to give the total emission reduction in tons/day statewide.

The fleet composite emission factor for 1988 is calculated using the age distribution of the fleet provided by CalTrans, and the emission factor data found in Tables 2-7 and 2-8. The CalTrans age distribution is summarized in Table 2-27. This distribution was multiplied by the emission factor data to arrive at the fleet composite emission factor shown in Table 2-28. A similar computation was performed to determine the fleet composite emission reductions listed in Table 2-29. The totals listed in Table 2-28 are the respective light and medium HDGT emission factors for the 1988 calendar year. The totals listed in Table 2-29 are the respective light and medium HDGT emission reductions due to I/M.

The totals from Table 2-28 and 2-29 are multiplied to determine the emission reduction due to the I/M program in grams/mile. Table 2-30 lists the reductions in grams/mile and tons/day statewide. As this table shows, the reduction in total NOx emissions from the light heavy fleet is approximately the same as for the medium heavies. In contrast, the reduction in CO emissions is approximately 500% greater for the medium HDGT fleet than for the light HDGT, and for HC, the reduction is approximately 300% greater. This is due to the greater I/M failure rate, higher VMT per vehicle, and greater emissions per VMT by the medium heavy fleet, which more than outweighed the greater number of light heavy-duty vehicles.

TABLE 2-27. AGE DISTRIBUTION OF HEAVY-DUTY GASOLINE FLEET IN 1988

	GASOLINE FLEET SIZE 1988			PERCENTAGE OF FLEET 1988	
Model Year	LIGHT HEAVY	MEDIUM HEAVY	Model Year	LIGHT HEAVY	MEDIUM HEAVY
1967	5906	22596	1967	2.39	15.71
1968	5000	5000	1968	2.02	3.48
1969	3995	5591	1969	1.61	3.89
1970	4257	4967	1970	1.72	3.45
1971	4325	3901	1971	1.75	2.71
1972	6595	6124	1972	2.66	4.26
1973	8012	7075	1973	3.24	4.92
1974	5805	6378	1974	2.34	4.43
1975	8819	6556	1975	3.56	4.56
1976	12207	5280	1976	4.93	3.67
1977	22864	6717	1977	9.24	4.67
1978	21013	7401	1978	8.49	5.15
1979	22740	8450	1979	9.19	5.87
1980	10823	4861	1980	4.37	3.38
1981	10488	3245	1981	4.24	2.26
1982	9206	2298	1982	3.72	1.60
1983	9227	1882	1983	3.73	1.31
1984	13920	5468	1984	5.62	3.80
1985	17216	9057	1985	6.95	6.30
1986	15339	6651	1986	6.20	4.62
1987	16583	7845	1987	6.70	5.45
1988	13233	6504	1988	5.35	4.52
TOTALS	247573	143847	TOTALS	100	100

TABLE 2-28. FLEET COMPOSITE EMISSIONS

	FLEET COMPOSITE EMISSIONS LIGHT HEAVY				FLEET COMPOSITE EMISSIONS MEDIUM HEAVY		
	HC	CO (gm/mile)	NOx		HC	CO (gm/mile)	NOx
TOTAL	5.20	112.09	4.74	TOTAL	12.95	241.44	8.34

TABLE 2-29. FLEET COMPOSITE EMISSION REDUCTIONS

	LIGHT HEAVY				MEDIUM HEAVY		
	HC	CO	NOx		HC	CO	NOx
TOTALS	7.95%	3.85%	0.87%	TOTALS	11.04%	9.19%	0.69%

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TABLE 2-30. 1988 EMISSIONS REDUCTIONS DUE TO I/M

	LIGHT HEAVY-DUTY			MEDIUM HEAVY-DUTY	
	GM/MI	TONS/DAY		GM/MI	TONS/DAY
HC	0.41	3.48	HC	1.43	11.3
CO	4.32	36.37	CO	22.20	174.99
NO_x	0.04	0.35	NO_x	0.06	0.46

TABLE 2-31. 1995 EMISSIONS REDUCTIONS DUE TO I/M

	LIGHT HEAVY-DUTY			MEDIUM HEAVY-DUTY	
	GM/MI	TONS/DAY		GM/MI	TONS/DAY
HC	0.23	2.14	HC	0.73	7.0
CO	2.49	23.10	CO	9.81	93.89
NO_x	0.07	0.63	NO_x	0.09	0.82

Table 2-31 lists the reductions for the different fleets expected in 1995. The trends for 1995 are approximately the same as those for 1988. The reduction in emissions due to I/M in 1995 is approximately two-thirds of the 1988 reduction. This is due to the reduced baseline emissions expected for the 1995 fleet. Slightly lower I/M failure rates were used for the 1995 model since it is expected that the failure rate will decline as the program continues. This trend has been observed with the Portland HDGV I/M program.

3.0 FEASIBILITY OF IMPLEMENTING A HEAVY-DUTY GASOLINE TRUCK INSPECTION AND MAINTENANCE PROGRAM

This section of the report reviews the results of studies undertaken to determine the feasibility of implementing a HDGT I/M program for the State of California. Studies were undertaken to determine the ability of the current Smog Check stations to test HDGTs, in addition to investigating the degree of interest in self-inspection for fleets. Heavy-duty truck repair stations were also contacted to determine if they would be interested in performing Smog Checks on HDGTs in addition to repairing them. The results of these surveys will be reviewed first.

Cost estimates of heavy-duty gasoline truck emission system repairs were also made. These estimates were arrived at by surveying HDGT repair stations to determine the retail cost of various emission and fuel system components, in addition to quantifying the labor rates for HDGT service. Estimates for the average cost of various repairs have been made. The cost-effectiveness of requiring the HDGT fleet to be "Smog Checked" is also discussed.

Finally, the current TAS analyzers used in the Smog Check Program were evaluated to determine if any modifications to them would be required to implement a HDGT I/M program. Suggested changes and modifications are discussed in the following section.

A decentralized program was used as the model for this section. The decentralized program was chosen since the California legislature has implemented this program for the light-duty vehicle fleet. It is expected that the same type of program would be implemented for the heavy-duty vehicle fleet. Decentralized programs do not tend to be as effective as centralized I/M programs. The advantages of centralized programs include: lower inspection costs due to the higher volume of vehicles per facility, reduced enforcement requirements since there are fewer facilities to inspect, and potentially higher quality inspections since the tests would be performed by a small number of highly trained technicians.

One of the most effective I/M programs in the nation is the Portland, Oregon centralized I/M program. In Portland, heavy-duty and light-duty gasoline vehicles are required to participate in the program. The Portland program does not have cost limits. All vehicles must be tested at the central facility and no waivers for cost exceedance are given. If the vehicle fails the I/M test it must be repaired and brought back to the central facility for a retest. With this program, vehicles which do not meet the standards are brought into compliance or they are not allowed to be registered.

The potential cost limit for a HDGT I/M program was also based on the current light-duty vehicle I/M program. The use of this limit as the basis for estimating costs does not imply that Radian feels the current cost limits are effective. This limit was chosen since it is currently in use and cannot be changed unless the legislature approves of an increase.

3.1 Testing Considerations

Radian conducted a telephone survey of California licensed Smog Check stations located throughout the Sacramento, Los Angeles, San Francisco, and Fresno areas. The survey was used to gather information to determine the feasibility of including heavy-duty gasoline powered trucks in the Smog Check Program. A summary of the responses from the surveyed Smog Check stations is presented in Table 3-1. The table provides a summary of the areas surveyed, as well as the average for the state. A sample questionnaire and the survey responses are presented in Appendix B.

As shown in the table, 84 percent of the Smog Check stations contacted indicated that they would be interested in performing Smog Checks on HDGTs. Moreover, 84 percent indicated that they have adequate space to Smog Check HDGTs. Only the Smog Check stations in the San Francisco area displayed a

TABLE 3-1

SUMMARY OF SURVEY RESPONSES FROM SMOG CHECK STATIONS

Descriptions	Fresno	Los Angeles	Sacramento	San Francisco	TOTAL/AVG.
	Smog Check Locations				
Number of facility responses	14	138	34	22	208
Percent that repair HDGT	71%	58%	59%	32%	56%
Percent interested in HDGT Smog Checks	79%	91%	82%	45%	84%
Percent with adequate space	86%	90%	79%	50%	84%
Average labor rate for LD vehicles	$38/hr	$32/hr	$39/hr	$49/hr	$40/hr
Average labor rate for HDGT	$38/hr	$40/hr	$41/hr	$56/hr	$44/hr
Number of HDGT that could be Smogged/day	5	6	12	10	8

KEY: HDGT - heavy-duty gasoline powered truck
LD - light-duty

great disinterest in performing HDGT Smog Checks (only 45 percent were interested). This is primarily due to the small lots in downtown San Francisco. At these lots, they would have to shuffle cars around to clear space for the HDGTs.

Radian also conducted a telephone survey of heavy-duty truck repair stations located in the Sacramento area. These repair stations indicated that they primarily repair diesels. Occasionally, they work on gasoline powered trucks. From this survey, heavy-duty truck repair stations indicated that they are not interested in performing emission tests (Smog Checks) on heavy-duty vehicles.

Radian also investigated the degree of interest in the self-inspection alternative for fleet operators. Approximately 20 fleet operators in California were contacted by telephone. Nearly half of these indicated that their fleet consisted of only diesel trucks. Of the fleet operators that have HDGTs, 85 percent are interested in self-inspections. One fleet operator stated it would depend on the fleet size and the cost-effectiveness. Several fleet operators currently self-inspect the vehicles that weigh less than 8500 lbs. GVW in their fleet. Many fleets with HDGTs also have LDV fleets. The addition of the HDGT fleet to the I/M program would increase the number of fleets eligible for self-inspection.

The emission control technology on HDGTs is not as sophisticated as on post-1980 model year light duty vehicles (LDV). The technology for HDGTs is similar to the 1975-1979 and pre-1975 model year LDVs. Therefore, mechanics should be able to adjust readily to repairing HDGTs. Moreover, from the Smog Check station survey, 56 percent of the stations repair heavy-duty gas trucks already. However, a small percentage of these stations do not repair the emission controls systems on HDGTs.

3.2 Estimation of Repair Costs

The cost estimates for heavy-duty gas truck repairs are based on the repairs performed on vehicles in the ARB I/M Evaluation Program. Based on data from the ARB I/M Evaluation Program repairs have been identified which yield significant emission benefits (Sierra Research, 1986). The following types of repairs were the most significant in terms of emission benefits:

'75-'79 Models	Pre-'75 Models
- adjust A/F ratio;	- correct misfires;
- correct misfires;	- connect vacuum lines;
- replace emissions components;	- adjust A/F ratio;
- repair vacuum leaks;	- adjust timing;
	- carb rebuild;

It is expected that these repairs will result in similar benefits for the HDGT fleet due to the similarity in emission control technology.

A summary of estimated emission control system repair costs for light-duty vehicles (LDVs) is provided in Table 3-2. Radian also conducted a telephone survey of over 200 licensed Smog Check stations throughout the State of California. From this survey, the average labor rate for light-duty vehicles is $40.00 per hour. This labor rate equals the labor rate (labor cost÷ labor time) in Table 3-2. From the same survey, the average labor rate for heavy-duty trucks increased by $4.00 dollars to about $44.00/hour. This means the labor cost would be greater for trucks if the labor time remained constant.

The emission control systems on heavy-duty gas trucks are not as sophisticated as those found on current model light duty vehicles. However, due to the size and configuration of some trucks, repairs on trucks can be more time consuming than light-duty vehicles.

TABLE 3-2. SUMMARY OF EMISSION CONTROL SYSTEM REPAIR COSTS FOR LIGHT-DUTY VEHICLES

	Labor Time (hrs)	Labor Cost ($)	Part Cost Domestic ($)	Part Cost Import ($)
Secondary Air				
Air Pump	0.6	24	150	290
Diverter Valve	0.7	28	45	65
Reed Valve (Pulse Air)	0.5	20	26	100
Exhaust Check Valve	0.3	12	24	24
Vacuum Control for Diverter Valve (TVS or solenoid)				
TVS	0.4	16	28	
Solenoid	0.6	24	65	
Carburetor				
Choke adjustment	0.6	24	n/a	
Choke Pulloff	0.7	28	25	18
Clean and adjust idle	0.5	20	n/a	
Mixture Control solenoid	0.7	28	50	60
Replace as unit	1.1	44	360 (775)	400
Fuel Injection				
Clean Injectors	0.5	20	n/a	
Replace Injector	1.1	44	58 (160)**	80

** TBI injector

Continued

TABLE 3-2. SUMMARY OF EMISSION CONTROL SYSTEM REPAIR COSTS FOR LIGHT-DUTY VEHICLES (Continued)

	Diagnostic Labor (hrs)	Replacement Labor (hrs)	Labor Cost ($)	Part Cost	
				Domestic ($)	Import ($)
Control System Sensors					
Air flow sensor	0.5	0.7	48	200	350
Coolant temp. sensor	0.5	0.2	28	20	17
Air temp. sensor	0.5	0.3	32	19	23
Throttle position sensor	0.5	0.3	32	40	50
Crankshaft position sensor	0.5	0.5	40	36	40
Oxygen sensor	0.3	0.5	32	50	150
Manifold Pressure sensor	0.5	0.4	36	55	120
Electronic Control unit	0.5	0.3	32	300	500
Wiring Harness				Variable	
EGR					
Backpressure valve	0.3	0.3	24	58	70
Clean orifice		0.3-0.4	12-16	n/a	
Electronic vacuum modulator				43.25	
TVS or solenoid					
TVS				10	12
Solenoid				65	58
Heated Air Intake Control Valve	0.2	0.2	16	15	10
Evaporative Canister Purge Valve				14	
Catalyst					
Three-way catalyst				300	500
Three-way + oxidation catalyst				385	---

Reference: Sierra Research, Inc., Evaluation of the California Smog Check Program, November, 1986.

Very few heavy-duty gas trucks have been equipped with catalytic converters, fuel injection systems, or oxygen sensors. Therefore, common emission repairs for HDGTs would include carburetor adjustments, ignition timing adjustments, replacement of spark plugs, and replacement of plug wire sets. A summary of repair costs for heavy-duty gas trucks is presented in Table 3-3. The labor times are based on ranges identified for Chevrolet, Ford, and GMC medium and heavy-duty truck times in the Motor Parts and Times Guide (Motor Manuals, 1986). The average labor rate for heavy-duty trucks from the Smog Check station survey was used to estimate labor costs. Heavy-duty truck dealers were contacted to determine parts costs.

For light-duty vehicles most repairs cannot be performed for less than the current cost ceiling of $50.00. The same is true for the HDGT fleet--the majority of repairs for HDGTs could not be performed separately for less than the $50.00 repair cost ceiling. In addition, if combinations of repairs were required, the cost of repairs would usually exceed the $50.00 cost ceiling. For example, the most common repair of trucks would include carburetor and timing adjustments. The cost for this repair ranges from $26.00 to $57.00. The Smog Check station survey showed an average cost of $30.00 for carburetor and/or timing adjustments for HDGTs. Another common repair scenario includes replacement of spark plugs. This repair cost ranges from $44.00 to $62.00. Other combinations of repairs would considerably exceed $50.00. The repair cost ceiling does not apply when repairing any system that has been tampered with, however.

Based solely on this information, it is hard to determine what fraction of the HDGTs could be repaired for less than the current $50.00 repair cost ceiling. This question was completed by 40% of the licensed Smog Check stations surveyed. They believe, on the average, that nearly 65% of the trucks requiring repairs could be repaired for less than $50.00. In the remaining cases, partial repairs might be possible within the $50.00 limit, or the owner might opt to pay more than the minimum to have the vehicle fully repaired. An

TABLE 3-3. SUMMARY OF REPAIR COSTS FOR HEAVY-DUTY GAS TRUCKS

Repair Descriptions	Labor Time (hrs)	Labor Cost (dollars)	Average Labor Cost (dollars)	Average Part Cost (dollars)	Average Total Cost (dollars)
Ignition Tune-up, Major (1)	2.7 - 4.2	119 - 185	152		152
Ignition Tune-up, Minor (2)	1.4 - 2.0	62 - 88	75		75
Spark Plugs, R&R or Renew	0.6 - 1.0	26 - 44	35	18	53
Plug Wire Set, Renew	0.4 - 0.8	18 - 35	26	40	66
Cap &/or Rotor, R&R or Renew	0.2 - 0.6	9 - 26	18	12/4	34
Ignition Timing, Adjust	0.3 - 0.6	13 - 26	20		20
PCV Valve, Renew	0.2 - 0.3	9 - 13	11	3	14
Air Inject, Pump, R&R or Renew	0.4 - 0.8	18 - 35	26	150	176
Diverter Valve, Renew	0.2 - 0.4	9 - 18	13	35	48
Carburetor, Adjust (3)	0.3 - 0.7	13 - 31	22		22
Carburetor, R&R or Renew	0.5 - 1.1	22 - 48	35	360 (700)	395
Carburetor Overhaul (4)	1.6 - 2.8	70 - 123	97		97

Key: R&R - remove and replace the same part.
Renew - remove the old part and install a new one.
Overhaul - remove an assembly from the truck, inspect, disassemble, repair, reassemble, install, and adjust.

Notes:

(1) Includes: check compression, clean or renew spark plugs, pick-up coil points condensers, cap and check coil. Check heat control valve and emission control systems. Includes use of stroboscope.
(2) Includes: renew points, pick-up coil condenser and plugs, set timing and adjust carburetor idle.
(3) Includes: using exhaust gas analyzer and tachometer, can be used with all carburetor repair operations when limiter cap removal is required.
(4) Includes: R&R carburetor and replace all parts furnished in kit. Clean air cleaner.

increase in this cost limit would certainly result in more effective repairs, however.

3.3 Cost-Effectiveness

The cost-effectiveness of the I/M program for a given year is determined by dividing the estimated cost of the I/M program by the annual emission reduction attributed to the program. The assumptions used in determining the annual emission reduction are described in detail in Chapter Two. In general, the emission reduction is equivalent to the aggregate I/M failure rate multiplied by the aggregate emission reduction due to repair. It was assumed that the deterioration of the repaired vehicles is no different than the general fleet. It is also assumed that the entire fleet is participating in the I/M program, and therefore emission reductions can be attributed to the entire fleet.

Based on the foregoing calculations, Radian estimated the cost-effectiveness of a HDGT I/M program for emissions control. Table 3-4 shows the results of this calculation for light heavy-duty trucks in 1988, while Table 3-5 shows it for medium heavy-duty vehicles in the same year. Table 3-6 and 3-7 show the results of the calculation for both the light and medium heavy-duty trucks in 1995. To develop these estimates, it was assumed that the average cost of inspection for heavy-duty vehicles would be about the same as the current average for light-duty vehicles--about $20.00. The cost of the emissions certificate was also assumed to be the same at $5.00. As the current Smog Check Program is self-financing, the certificate fee was assumed to be sufficient to cover all of the State's expenses in administering the program. Making this assumption, the cost of the program to the consumer and the cost to society as a whole can be assumed to be equal.

The failure rates and emission reductions due to repairs shown in the Tables were taken from the discussion in the previous chapter. The average cost of repairs in the program was assumed to be similar to the average cost of

TABLE 3-4. COST-EFFECTIVENESS ANALYSIS

1988 LIGHT HEAVY-DUTY VEHICLES

PERCENT OF FLEET FAILING 22.35

	COSTS/VEHICLE		
	PASSING	FAILING	AVERAGE
Inspection	$20.00	$20.00	$20.00
Certificate	$5.00	$5.00	$5.00
Repairs and Reinspection		$36.21 $6.00	$8.09 $1.34
TOTAL	$25.00	$67.21	$34.43
COST/YEAR	$12.50	$33.61	$17.22

TOTAL COSTS AND EMISSIONS REDUCTIONS
FOR CALIFORNIA (247,573 light heavy-duty gasoline trucks)

PROGRAM COST		$4,300,000
EMISSION REDUCTION		
	HC	3.48 TONS/DAY
	CO	36.37 TONS/DAY

COST-EFFECTIVENESS FOR LIGHT HEAVY-DUTY

CREDIT FOR HC	$0.85 PER POUND
CREDIT FOR CO	$0.08 PER POUND

TABLE 3-5. COST-EFFECTIVENESS ANALYSIS

1988 MEDIUM HEAVY-DUTY VEHICLES

PERCENT OF VEHICLES FAILING 31.23

	COSTS/VEHICLE PASSING	FAILING	AVERAGE
Inspection	$20.00	$20.00	$20.00
Certificate	$5.00	$5.00	$5.00
Repairs and		$36.21	$11.31
Reinspection		$6.00	$1.87
TOTAL	$25.00	$67.21	$38.18
COST/YEAR	$12.50	$33.61	$19.09

TOTAL COSTS AND EMISSIONS REDUCTIONS
FOR CALIFORNIA (143847 medium heavy-duty gasoline trucks)

PROGRAM COST $2,700,000

EMISSION REDUCTION

HC	11.27	TONS/DAY
CO	174.99	TONS/DAY

COST-EFFECTIVENESS FOR MEDIUM HEAVY-DUTY

CREDIT FOR HC	$0.16 PER POUND
CREDIT FOR CO	$0.01 PER POUND

COST-EFFECTIVENESS
FOR LIGHT AND MEDIUM HEAVY COMBINED

CREDIT FOR HC	$0.33 PER POUND
CREDIT FOR CO	$0.02 PER POUND

TABLE 3-6. COST-EFFECTIVENESS ANALYSIS

1995 LIGHT HEAVY-DUTY VEHICLES

PERCENT OF VEHICLES FAILING 19.94

	COSTS/VEHICLE PASSING	FAILING	AVERAGE
Inspection	$20.00	$20.00	$20.00
Certificate	$5.00	$5.00	$5.00
Repairs and		$36.21	$7.22
Reinspection		$6.00	$1.20
TOTAL	$25.00	$67.21	$33.42
COST/YEAR	$12.50	$33.61	$16.71

TOTAL COSTS AND EMISSIONS REDUCTIONS
FOR CALIFORNIA (274,667 light heavy-duty gasoline trucks)

PROGRAM COST		$4,600,000
EMISSION REDUCTION		
	HC	2.14 TONS/DAY
	CO	23.10 TONS/DAY

COST-EFFECTIVENESS FOR LIGHT HEAVY-DUTY

CREDIT FOR HC	$1.48 PER POUND
CREDIT FOR CO	$0.14 PER POUND

TABLE 3-7. COST-EFFECTIVENESS ANALYSIS

1995 MEDIUM HEAVY-DUTY VEHICLES

PERCENT OF VEHICLES FAILING 25.47

COSTS/VEHICLE

	PASSING	FAILING	AVERAGE
Inspection	\$20.00	\$20.00	\$20.00
Certificate	\$5.00	\$5.00	\$5.00
Repairs and		\$36.21	\$9.22
Reinspection		\$6.00	\$1.53
TOTAL	\$25.00	\$67.21	\$35.75
COST/YEAR	\$12.50	\$33.61	\$17.88

TOTAL COSTS AND EMISSIONS REDUCTIONS
FOR CALIFORNIA (142785 medium heavy-duty gasoline trucks)

PROGRAM COST		\$2,550,000
EMISSION REDUCTION	HC	6.98 TONS/DAY
	CO	93.89 TONS/DAY
COST-EFFECTIVENESS	CREDIT FOR HC	\$0.25 PER POUND
	CREDIT FOR CO	\$0.02 PER POUND

COMBINED COST-EFFECTIVENESS
LIGHT AND MEDIUM HEAVY-DUTY GASOLINE TRUCKS

CREDIT FOR HC	\$0.54 PER POUND
CREDIT FOR CO	\$0.04 PER POUND

repairs for light-duty vehicles, obtained from the TAS data for March, 1986, by Sierra Research. This average was $36.21, indicating that the cost of many repairs is running well below the $50.00 limit.

The costs of inspection and repairs per vehicle were divided by two to get the annual costs per vehicle (reflecting the biennial inspection schedule for the Smog Check Program). These were multiplied by the total number of vehicles to give the total costs of the program, then divided into the total emissions reduction to give costs per pound. Since the Smog Check program affects emissions of all three pollutants (HC, CO, and NOx), it was necessary to allocate the costs of the program accordingly. For the calculations in Tables 3-4, 3-5, 3-6, and 3-7 half of the program costs were allocated to HC reduction, and half to CO reduction, with no cost allocated to reducing NOx, since the NOx reduction due to the Smog Check is small.

With these assumptions, the calculated cost-effectiveness of I/M in 1988 for medium heavy-duty vehicles is $0.16/pound for HC and $0.01/pound for CO, while for light-heavy-duty vehicles it is $0.85/pound for HC and $0.08/pound for CO. The much greater cost-effectiveness of I/M for medium-heavy vehicles is due both to the higher failure rate projected and to the greater emissions per year from these vehicles. The cost-effectiveness of a combined program, inspecting both medium-heavy and light-heavy vehicles, is estimated at $0.33/pound for HC and $0.02/pound for CO.

All of these values compare very favorably with the cost-effectiveness of the current Smog Check Program, and with most other sources of HC and CO emissions control. In a recent report (Jacobs and Weaver, 1986), Radian estimated the cost-effectiveness of the Smog Check Program for light-duty vehicles as $1.35/pound for HC, and $0.12/pound for CO, using a similar calculation.

The calculated cost-effectiveness of I/M in 1995 for medium heavy-duty vehicles is $0.25/pound for HC and $0.02/pound for CO, while for light heavy-duty vehicles it is $1.48/pound for HC and $0.14/pound for CO. The much greater cost-effectiveness of I/M for medium-heavy vehicles is due to the slightly higher projected failure rate and the much greater emissions per year from these vehicles. The cost-effectiveness of a combined program, inspecting both medium and light heavy-duty vehicles, is estimated at $0.54/pound for HC and $0.04/pound for CO. Once again, these values compare favorably with the cost-effectiveness of the current Smog Check Program.

As a sensitivity check, cost-effectiveness values were also calculated assuming reduced failure rates and reduced emission reductions due to repair for both 1988 and 1995. Tables 3-8 and 3-9 show the cost-effectiveness for 1988 assuming the failure rates and emission reductions due to repair are only 70 percent of the previously used values. This value was chosen since the current evaluations of the light-duty vehicle I/M program show it to be operating at approximately 70% efficiency. The spreadsheets of the failure rates and emission reduction due to repair with this scenario can be found in Appendix C. The cost-effectiveness is approximately halved when the I/M program is only 70 percent as effective as predicted in chapter 2.0. Even with the significant reduction in cost-effectiveness, the program is still competitive with the light-duty vehicle I/M program.

Tables 3-10 and 3-11 show the results of reduced failure rates and emission reductions due to repair on the cost-effectiveness in 1995. The combined cost-effectiveness in 1995 is $0.99/pound for HC and $0.08/pound for CO. The HDGV I/M program's efficiency is also reduced in 1995, but it is still competitive with the light-duty vehicle I/M program's cost-effectiveness.

3.4 Investigation of Test Analyzer System Changes

The current test analyzer system (TAS) used to Smog Check light-duty vehicles stores test information and results on cassette tapes. All of the information required for differentiating heavy-duty gas trucks from light-duty vehicles is already included in the automatic data collection unit of the TAS.

TABLE 3-8. COST-EFFECTIVENESS ANALYSIS

1988 LIGHT HEAVY-DUTY VEHICLES
REDUCED I/M EFFECTIVENESS

PERCENT OF VEHICLES FAILING 15.85

COSTS/VEHICLE

	PASSING	FAILING	AVERAGE
Inspection	$20.00	$20.00	$20.00
Certificate	$5.00	$5.00	$5.00
Repairs and Reinspection		$36.21	$5.74
		$6.00	$0.95
TOTAL	$25.00	$67.21	$31.69
COST/YEAR	$12.50	$33.61	$15.84

TOTAL COSTS AND EMISSIONS REDUCTIONS
FOR CALIFORNIA (247,573 light heavy-duty gasoline trucks)

PROGRAM COST		$3,900,000
EMISSION REDUCTION		
	HC	1.74 TONS/DAY
	CO	17.83 TONS/DAY
COST-EFFECTIVENESS FOR LIGHT HEAVY-DUTY		
	HC	$1.54 PER POUND
	CO	$0.15 PER POUND

TABLE 3-9. COST-EFFECTIVENESS ANALYSIS

1988 MEDIUM HEAVY-DUTY VEHICLES
REDUCED I/M EFFECTIVENESS

PERCENT OF VEHICLES FAILING 21.88

	COSTS/VEHICLE PASSING	FAILING	AVERAGE
Inspection	$20.00	$20.00	$20.00
Certificate	$5.00	$5.00	$5.00
Repairs and		$36.21	$7.92
Reinspection		$6.00	$1.31
TOTAL	$25.00	$67.21	$34.24
COST/YEAR	$12.50	$33.61	$17.12

TOTAL COSTS AND EMISSIONS REDUCTIONS
FOR CALIFORNIA (143847 medium heavy-duty gasoline trucks)

PROGRAM COST		$2,500,000
EMISSION REDUCTION	HC	5.56 TONS/DAY
	CO	85.83 TONS/DAY

COST-EFFECTIVENESS FOR MEDIUM HEAVY-DUTY

CREDIT FOR HC	$0.31 PER POUND
CREDIT FOR CO	$0.02 PER POUND

COST-EFFECTIVENESS
FOR LIGHT AND MEDIUM HEAVY COMBINED

CREDIT FOR HC	$0.60 PER POUND
CREDIT FOR CO	$0.04 PER POUND

TABLE 3-10. COST-EFFECTIVENESS ANALYSIS

1995 LIGHT HEAVY-DUTY VEHICLES
REDUCED I/M EFFECTIVENESS

PERCENT OF VEHICLES FAILING 13.91

COSTS/VEHICLE

	PASSING	FAILING	AVERAGE
Inspection	$20.00	$20.00	$20.00
Certificate	$5.00	$5.00	$5.00
Repairs and Reinspection		$36.21 $6.00	$5.04 $0.83
TOTAL	$25.00	$67.21	$30.87
COST/YEAR	$12.50	$33.61	$15.44

TOTAL COSTS AND EMISSIONS REDUCTIONS
FOR CALIFORNIA (274,667 light heavy-duty gasoline trucks)

PROGRAM COST		$4,200,000
EMISSION REDUCTION		
	HC	1.05 TONS/DAY
	CO	11.16 TONS/DAY

COST-EFFECTIVENESS FOR LIGHT HEAVY-DUTY

HC	$2.75 PER POUND
CO	$0.26 PER POUND

TABLE 3-11. COST-EFFECTIVENESS ANALYSIS

1995 MEDIUM HEAVY-DUTY VEHICLES
REDUCED I/M EFFECTIVENESS

PERCENT OF VEHICLES FAILING 17.89

	COSTS/VEHICLE PASSING	FAILING	AVERAGE
Inspection	$20.00	$20.00	$20.00
Certificate	$5.00	$5.00	$5.00
Repairs and		$36.21	$6.48
Reinspection		$6.00	$1.07
TOTAL	$25.00	$67.21	$32.55
COST/YEAR	$12.50	$33.61	$16.28

TOTAL COSTS AND EMISSIONS REDUCTIONS
FOR CALIFORNIA (142785 medium heavy-duty gasoline trucks)

PROGRAM COST		$2,300,000
EMISSION REDUCTION		
	HC	3.44 TONS/DAY
	CO	46.26 TONS/DAY

COST-EFFECTIVENESS FOR MEDIUM HEAVY-DUTY

CREDIT FOR HC	$0.46 PER POUND
CREDIT FOR CO	$0.03 PER POUND

COMBINED COST EFFECTIVENESS
LIGHT AND MEDIUM HEAVY-DUTY GASOLINE TRUCKS

CREDIT FOR HC	$0.99 PER POUND
CREDIT FOR CO	$0.08 PER POUND

A useful change to the TAS software would be the inclusion of vehicle make abbreviations for HDGTs. This menu should be standardized so that entry errors by the operators would be caught by the TAS. With the current method for entering the truck vehicle make, errors could go undetected according to the California Bureau of Automotive Repair specification. Including the HDGTS vehicle make list should not be a major task since the majority of HDGT are produced by LDV manufacturers.

Including the HDGT vehicle make abbreviation menu included in the TAS system would simplify entering the vehicle make for the mechanic. Currently, the Smog Mechanic enters the vehicle type and gross vehicle weight of the vehicle being tested prior to selecting the vehicle make abbreviation. If the mechanic responds that the vehicle is a truck and its GVW is greater than 8500 lb., then the HDGT vehicle make abbreviation list should be displayed by the TAS. This would allow the TAS to use the same information field for storing the HDGT make as is currently used to store the LDV make. The advantage of this method is that no additional modifications are required to the cassette recorder format specification. In addition, the HDGT fleet can be added to the TAS system without increasing the size of cassette data record.

The emission standards for the HDGTs will most likely not be the same as the LDVs. Therefore, other modifications will be required to the software in order to include emission standards for the HDGTs.

The only other modification that might be required is to extend the length of the cord for the engine speed probe. No maximum length is specified in the BAR '84 specifications, however a minimum length of 25 feet is noted. For some HDGVs, especially recreational vehicles, 25 feet is not long enough to allow the engine speed to be recorded while the emissions probe is in the exhaust pipe. The speed probe could readily be extended to accommodate vehicles 40 feet long, which is the maximum vehicle length permitted by law (Nase et al., 1986).

4.0 ANALYSIS OF ADMINISTRATIVE ISSUES

This section analyzes the administrative issues that would need to be addressed prior to implementing an I/M program for heavy-duty gasoline trucks. In general, these issues closely resemble those which have already been addressed in implementing the existing Smog Check Program for light-duty vehicles. Some of the issues to be discussed include the cost limits of the program, TAS upgrades, program enforcement, and the setting of emission standards.

With the experience of the LDV I/M program as a basis, the State of California should readily be able to organize, develop, and promote a heavy-duty gasoline I/M program. Adding HDGVs to the existing LDV I/M program would not significantly increase the work load upon current Smog Check stations. In 1988, it is expected that the entire HDGT fleet will consist of approximately 400,000 vehicles. This is only 3% of the existing fleet of vehicles required to participate in the Smog Check Program.

The goals and regulations of the HDGT I/M program should be based on the experience obtained from the LDV I/M program. The operation of the HDGT I/M program could be easily tied into the LDV I/M program. As was shown from the survey of the Smog Check stations, most stations would be willing to work on HDGTs. The enforcement aspects of the program could be performed similarly to the LDV I/M program. Making the registration and licensing of the vehicle dependent upon the display of a Certificate of Conformance (as is presently the case for LDVs) would serve as an effective means of enforcement.

As discussed previously, no major changes would be required to the TAS analyzers to add HDGVs to the Smog Check Program. The addition of a standard menu for the HDGT make and different emission standards would be required. Lengthening the cord for the engine speed probe will be necessary to test vehicles which are 40 feet in length.

The mechanics currently working on LDV emission systems should easily adjust to working on HDGTs. The HDGT fleet has not seen the use of electronic fuel injection, or closed loop fuel control systems. The majority of these trucks are similar to 1974 and older LDVs, which are easier for the mechanics to troubleshoot and repair than current-technology electronically-controlled vehicles.

Cost Limits

Under the current Smog Check Program, the maximum cost that the consumer is required to pay to repair his/her vehicle is currently fifty dollars (unless tampering is present). The Smog Check legislation allows this maximum to be increased to no more than one hundred dollars. In other reports, this limit has been shown to be too low to permit repair of most recent model light-duty vehicles. In this report it has been shown that for the current level of technology in HDGTs, the fifty dollar limit will repair only a few of the minor problems. If more than one problem is found with the vehicle, the cost to repair the vehicle will be greater than the fifty dollar limit.

The current technology level of HDGTs is equivalent to the 1975-1979 LDVs but will begin to approach that of the later model vehicles in the future. As this advancement in the emission control technology occurs, the ability of a repair facility to fix a problem with the emission control system for under fifty dollars will decrease drastically. Currently, certain items cannot be repaired on HDGTs for less than the current LDV cost limit. If a carburetor or air injection pump needs replacing to bring the vehicle into compliance, both repairs exceed the current cost limit. Setting the cost ceiling to the $100.00 limit would allow more of the necessary repairs to be performed on HDGTs failing the "Smog Check".

Setting Emission Standards

The emission standards from thirteen different I/M programs that currently require HDGVs to participate were reviewed. No two heavy-duty gasoline I/M programs are alike with respect to the emission standards that are used and the vehicle model year's that are required to be tested. Table 4-1 is a summary of the hydrocarbon emission standards and model years to which they apply for the different I/M programs that were reviewed. Table 4-2 is a summary of the carbon monoxide emission standards and model years to which they apply for the different I/M programs.

The age of the vehicle is the one factor that is used by all administrators to determine the emission standard. Some programs also use the GVW of the vehicle as a discriminator to determine the emission standard. Most programs require the vehicle to meet a hydrocarbon and carbon monoxide standard in order to pass the test. Some programs, most notably the two Alaska I/M programs, require that the vehicle only meet a carbon monoxide standard. The majority of the programs require that the vehicle meet the emission standards when idling and when operating at a different engine speed.

From the review of the different programs, it appears that each program has individually determined the emission standards that will best suit their specific needs. Before determining the cutpoints for the California HDGV I/M program, the intent and goals of the program need to be determined. If the goal of the program is to fail each and every vehicle that is emitting at a rate greater than the certification standard, a very stringent emission standards strategy should be employed.

The program could also be designed to fail only vehicles that are emitting at rates significantly greater than the emission standard. Vehicles that were within 150 percent of the certification standard would be allowed to pass the I/M test with this goal. Another potential program goal would be to specify a given failure rate and base the emission standards on achieving the desired failure rate. Each of these goals would require a different emission standard strategy.

As has been mentioned before, very little work has been done to determine the emissions performance of the heavy-duty gasoline fleet. It is

TABLE 4-1. HYDROCARBON EMISSION STANDARDS FOR HEAVY-DUTY GASOLINE VEHICLES

	(PPM)									
	Pre-'70	'70-'71	'72-'73	'74-'75	'76-'77	'78-'79	'80-'81	'82-'83	'84-'85	'86+
Alaska	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Arizona	N/A	N/A	300-400	300-400	300-350	300-350	300	300	300	300
Colorado	1400	1400	1400	1400	1400	1000	1000	1000	1000	1000
Conneticut	850	700	700	500	500	300-500	300	300	300	300
Illinois	1500	1500	900	900	900	700-900	700	700	300-700	300
Louisville, KY	1550	1550	900	800-900	800	800	650	650	220	220
Maryland	N/A	N/A	1000	800-1000	650-800	500-650	300-500	300	300	300
New York	800	700	700	600	600	400-600	400	400	400	400
North Carolina	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Oregon	900	700	700	500	500	350-500	350	350	350	350
Pennsylvania	1500	800	800	650	650	650	650	650	650	650
Salt Lake Cy., UT	1500	1200	1200	1200	1200	1000-1200	1000	800	800	800
Utah County, UT	1900	1700	1700	1700	1700	1500-1700	1500	1200	1200	1200

TABLE 4-2. CARBON MONOXIDE EMISSION STANDARDS FOR HEAVY-DUTY GASOLINE VEHICLES

	(Percent)									
	Pre-'70	'70-'71	'72-'73	'74-'75	'76-'77	'78-'79	'80-'81	'82-'83	'84-'85	'86+
Alaska	N/A	5.0	5.0	4.0	4.0	3.0-4.0	3.0	3.0	3.0	3.0
Arizona	N/A	N/A	3.0-5.0	3.0-5.0	3.0-4.0	3.0-4.0	3.0-4.0	3.0-4.0	3.0-4.0	3.0-4.0
Colorado	7.0	6.0	6.0	6.0	6.0	5.0-6.0	3.5-4.0	3.5	3.5	3.5
Conneticut	7.0	5.5	5.5	4.0	4.0	3.0-4.0	3.0	3.0	3.0	3.0
Illinois	9.5	9.5	9.0	9.0	9.0	7.0-9.0	7.0	7.0	3.0-7.0	3.0
Louisville, KY	9.5	9.5	9.0	8.0-9.0	8.0	8.0	6.5	6.5	1.2	1.2
Maryland	N/A	N/A	9.0	8.0-9.0	6.5-8.0	5.0-6.5	3.0-5.0	3.0	3.0	3.0
New York	7.0	6.0	6.0	4.5	4.5	3.5-4.5	3.5	3.5	3.5	3.5
North Carolina	N/A	N/A	7.5	5.5	5.5	5.0-5.5	5.0	5.0	5.0	5.0
Oregon	4.0-6.5	3.0-5.0	3.0-5.0	3.0-4.0	3.0-4.0	3.0-4.0	3.0	3.0	3.0	3.0
Pennsylvania	7.0	6.5	6.5	6.0	6.0	6.0	6.0	6.0	6.0	6.0
Salt Lake Cy., UT	9.0	6.5	6.5	6.5	6.5	5.0-6.5	5.0	5.0	5.0	5.0
Utah County, UT	7.0	5.5	5.5	5.5	5.5	4.0-5.5	3.5-4.0	3.5	3.5	3.5

not expected that data similar to the New York study would be available to assist in setting the emission standards. It is known that no data exists that quantifies the emissions performance and idle emissions of the California HDGV fleet. Therefore, additional research and testing of a representative sample of HDGVs would be needed in order to set cupoints specific to California. Otherwise, the emission standards could be based either on experience with the LDV fleet, or analysis of the failure rates and emission standards used in other HDGV I/M programs.

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GLOSSARY OF TERMS, ABBREVIATIONS, AND SYMBOLS

AIR	-	Air Injection into the Exhaust Manifold
ARB	-	California Air Resources Board
BAR	-	California Bureau of Automotive Repair
BHP-hr/mile	-	Brake Horsepower - Hour/Mile
CO	-	Carbon Monoxide
CalTrans	-	California Department of Transportation
DVMT	-	Daily Vehicle Miles Travelled
EMFAC7C	-	ARB Model Used to Calculate Emission Factors
EPA	-	United States Environmental Protection Agency
gm/BHP-hr	-	Grams/Brake Horsepower-Hour
gm/mi	-	Grams/Mile
FTP	-	Federal Test Procedure
GVW	-	Gross Vehicle Weight
HC	-	Hydrocarbons
HDGT	-	Heavy-Duty Gasoline Truck
HDGV	-	Heavy-Duty Gasoline Vehicle
HDV	-	Heavy-Duty Vehicle
I/M	-	Inspection and Maintenance
IW	-	Intertia Weight
lb	-	Pounds
LDV	-	Light-Duty Vehicle
MPG	-	Miles per Gallon
MVMA	-	Motor Vehicle Manufacturer's Association
NO_x	-	Oxides of Nitrogen
O_2	-	Oxygen
RPM	-	Engine Speed in Revolutions per Minute
TAS	-	Test Analyzer System
VMT	-	Vehicle Miles Travelled

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APPENDIX A

TABLE A-1. DATA USED TO CALCULATE THE 1995 EMISSION FACTORS

Model Year	ZERO MILE (gm/BHP-hr) HC	CO	NOx	DETERIORATION FACTOR (gm/BHP-hr/10,000 mi) HC	CO	NOx	AVERAGE MILEAGE ACCUMULATED BY MODEL YEAR
1974	5.91	101	5	0.18	4.69	0.06	222000
1975	5.91	101	5	0.18	4.69	0.06	222000
1976	5.91	101	5	0.18	4.69	0.06	222000
1977	3	80	5	0.18	4.69	0.06	215000
1978	3	80	5	0.18	4.69	0.06	208000
1979	3	80	5	0.18	4.69	0.06	200000
1980	3	80	5	0.18	4.69	0.06	193000
1981	3	80	5	0.18	4.69	0.06	185000
1982	3	80	5	0.18	4.69	0.06	178000
1983	3	80	5	0.18	4.69	0.06	171000
1984	2.5	60	4.4	0.18	4.69	0.06	163000
1985	2.5	60	4.4	0.13	2.06	0.06	156000
1986	2.5	60	4.4	0.13	2.06	0.06	149000
1987	2.5	60	4.4	0.13	2.06	0.06	139000
1988	2.5	60	4.4	0.13	2.06	0.06	129000
1989	2.5	60	4.4	0.13	2.06	0.06	117000
1990	2.5	60	4.4	0.13	2.06	0.06	106000
1991	2.5	60	4.4	0.13	2.06	0.06	90500
1992	2.5	60	4.4	0.13	2.06	0.06	75400
1993	2.5	60	4.4	0.13	2.06	0.06	57400
1994	2.5	60	4.4	0.13	2.06	0.06	39400
1995	2.5	60	4.4	0.13	2.06	0.06	19700

TABLE A-2. 1995 HEAVY-DUTY GASOLINE TRUCK EMISSION RATES

Model Year	HC	(gm/BHP-hr) CO	NOx
1974	9.91	205.12	6.33
1975	9.91	205.12	6.33
1976	9.91	205.12	6.33
1977	6.87	180.84	6.29
1978	6.74	177.55	6.25
1979	6.60	173.80	6.20
1980	6.47	170.52	6.16
1981	6.33	166.77	6.11
1982	6.20	163.48	6.07
1983	6.08	160.20	6.03
1984	5.43	136.45	5.38
1985	4.53	92.14	5.34
1986	4.44	90.69	5.29
1987	4.31	88.63	5.23
1988	4.18	86.57	5.17
1989	4.02	84.10	5.10
1990	3.88	81.84	5.04
1991	3.68	78.64	4.94
1992	3.48	75.53	4.85
1993	3.25	71.82	4.74
1994	3.01	68.12	4.64
1995	2.76	64.06	4.52

TABLE A-3. 1995 LIGHT HEAVY-DUTY GASOLINE TRUCK EMISSION FACTORS

Model Year	HC	(gm/mile) CO	NOx
1974	8.62	178.45	5.51
1975	8.62	178.45	5.51
1976	8.62	178.45	5.51
1977	5.98	157.33	5.47
1978	5.87	154.47	5.44
1979	5.74	151.21	5.39
1980	5.63	148.35	5.36
1981	5.51	145.09	5.32
1982	5.40	142.23	5.28
1983	5.29	139.37	5.24
1984	4.73	118.71	4.68
1985	3.94	80.16	4.64
1986	3.86	78.90	4.61
1987	2.47	17.47	5.99
1988	2.37	17.17	5.89
1989	2.25	16.81	5.77
1990	2.14	16.48	5.66
1991	1.86	15.62	5.31
1992	1.73	15.19	5.18
1993	1.57	14.66	5.02
1994	1.38	13.66	4.73
1995	1.21	13.13	4.56

TABLE A-4. 1995 MEDIUM HEAVY-DUTY GASOLINE TRUCK EMISSION FACTORS

Model Year	HC	(gm/mile) CO	NOx
1974	13.74	284.48	8.78
1975	13.91	287.95	8.89
1976	14.16	293.14	9.05
1977	9.99	263.01	9.15
1978	9.91	260.91	9.18
1979	9.80	258.02	9.20
1980	9.71	255.71	9.23
1981	9.54	251.34	9.21
1982	9.40	247.63	9.19
1983	9.31	245.30	9.23
1984	8.41	211.18	8.32
1985	7.08	144.12	8.35
1986	6.85	140.05	8.17
1987	6.56	135.09	7.98
1988	6.22	128.91	7.70
1989	5.85	122.28	7.42
1990	5.50	116.12	7.15
1991	5.09	108.83	6.84
1992	4.69	101.87	6.54
1993	4.37	96.70	6.39
1994	4.05	91.55	6.23
1995	3.70	85.94	6.06

TABLE A-5. 1995 FAILURE RATES

Model Year	LIGHT HEAVY-DUTY GASOLINE TRUCKS (%)	MEDIUM HEAVY-DUTY GASOLINE TRUCKS (%)
1974	31	38
1975	31	38
1976	31	38
1977	31	38
1978	31	38
1979	31	38
1980	27	31
1981	27	31
1982	27	31
1983	27	31
1984	27	31
1985	23	27
1986	23	27
1987	23	27
1988	23	27
1989	16	21
1990	14	19
1991	13	17
1992	11	15
1993	9	13
1994	8	12
1995	7	11

Source: All model years - Anchorage, Alaska HDGT I/M Program Failure Rates provided by Sierra Research.

TABLE A-6. 1995 EMISSION REDUCTION DUE TO REPAIR
LIGHT HEAVY-DUTY GASOLINE TRUCKS

Model Year	HC	(%) CO	NO_x
1974	34	20	0
1975	37	16	5
1976	37	16	5
1977	37	16	5
1978	37	16	5
1979	37	16	5
1980	37	16	5
1981	37	16	5
1982	37	16	5
1983	37	16	5
1984	37	16	5
1985	37	16	5
1986	37	16	5
1987	23	20	10
1988	23	20	10
1989	23	20	10
1990	23	20	10
1991	23	20	10
1992	23	20	10
1993	23	20	10
1994	23	20	10
1995	23	20	10

RADIAN CORPORATION

TABLE A-7. 1995 EMISSION REDUCTION DUE TO REPAIR MEDIUM HEAVY-DUTY GASOLINE TRUCKS

Model Year	(%) HC	CO	NOx
1974	34	37	0
1975	34	20	5
1976	34	20	5
1977	34	20	5
1978	34	20	5
1979	34	20	5
1980	34	20	5
1981	34	20	5
1982	34	20	5
1983	34	20	5
1984	34	20	5
1985	34	20	5
1986	34	20	5
1987	34	20	5
1988	34	20	5
1989	34	20	5
1990	34	20	5
1991	34	20	5
1992	34	20	5
1993	34	20	5
1994	34	20	5
1995	34	20	5

TABLE A-8. AGE DISTRIBUTION OF THE HEAVY-DUTY GASOLINE FLEET IN 1995

	GASOLINE FLEET SIZE 1995			PERCENTAGE OF FLEET 1995	
Model Year	LIGHT HEAVY	MEDIUM HEAVY	Model Year	LIGHT HEAVY	MEDIUM HEAVY
1974	11876	13277	1974	4.32	9.30
1975	10000	15000	1975	3.64	10.51
1976	5383	2329	1976	1.96	1.63
1977	10575	3107	1977	3.85	2.18
1978	10302	3628	1978	3.75	2.54
1979	12093	4493	1979	4.40	3.15
1980	6221	2794	1980	2.26	1.96
1981	6493	2009	1981	2.36	1.41
1982	6117	1526	1982	2.23	1.07
1983	6555	1337	1983	2.39	0.94
1984	10535	4139	1984	3.84	2.90
1985	13822	7272	1985	5.03	5.09
1986	13008	5640	1986	4.74	3.95
1987	14023	6621	1987	5.11	4.64
1988	15063	7479	1988	5.48	5.24
1989	15923	8089	1989	5.80	5.67
1990	16712	8502	1990	6.08	5.95
1991	17480	8909	1991	6.36	6.24
1992	18116	9195	1992	6.60	6.44
1993	18715	9456	1993	6.81	6.62
1994	20016	10093	1994	7.29	7.07
1995	15639	7890	1995	5.69	5.53
TOTALS	274667	142785	TOTALS	100	100

TABLE A-9. FLEET COMPOSITE EMISSIONS

	1995 FLEET COMPOSITE EMISSIONS LIGHT HEAVY (gm/mile)				1995 FLEET COMPOSITE EMISSIONS MEDIUM HEAVY (gm/mile)		
	HC	CO	NOx		HC	CO	NOx
TOTAL	3.65	70.38	5.25	TOTAL	7.82	172.26	7.77

TABLE A-10. FLEET COMPOSITE EMISSION REDUCTIONS

	1995 FLEET EMISSION REDUCTIONS LIGHT HEAVY				1995 FLEET EMISSION REDUCTIONS MEDIUM HEAVY		
	HC	CO	NOx		HC	CO	NOx
TOTALS	6.31%	3.54%	1.30%	TOTALS	9.32%	5.69%	1.10%

RADIAN CORPORATION

APPENDIX B

RADIAN CORPORATION

SMOG CHECK STATIONS

1. Do you repair heavy-duty gasoline trucks? Heavy-duty trucks are greater than 8,500 lbs. GVW (i.e., vans, step vans, recreational vehicles, flat beds, trucks, buses).

2. Would you be interested in performing Smog Checks on heavy-duty gas trucks?

3. Do you have adequate space to inspect heavy-duty trucks? What is the longest size of truck you could inspect?

4. What physical constraints would effect Smog Checks and repairs of heavy-duty gas trucks?

5. What are your labor rates for light-duty vehicles (i.e., cars)?

6. Would the labor rates differ for heavy-duty trucks? If so, by how much?

7. What would repairs cost to adjust the carburetor and/or the ignition system for a heavy-duty truck?

8. What fraction of the heavy-duty trucks could be repaired for less than the $50 repair cost ceiling in the current I/M program?

9. Given your existing conditions, how many trucks could be Smog Checked per day?

10. How should the current Smog Check program be changed for heavy-duty vehicles? Do you have any suggestions?

RADIAN CORPORATION

SURVEY SUMMARY OF SMOG
CHECK STATIONS

QUESTION	SAC 1	SAC 2	SAC 3	SAC 4	SAC 5	SAC 6	SAC 7	SAC 8	SAC 9
1. REPAIR H-D TRUCKS	YES	YES	YES	NO	YES	YES	NO	YES	YES
2. INTERESTED	YES	YES	YES	NO	YES	YES	NO	YES	YES
3. ADEQUATE SPACE	YES	YES	YES	NO	YES	YES	NO	NO	YES
MAX. LENGTH		35 - 40 ft	32 ft		20 ft	36 ft	50 ft	24 ft	12 - 20 ft
4. PHYSICAL CONSTRAINTS	NONE	13 ft CLEARANCE	NONE	SIZE	HEIGHT	12 ft CLEARANCE	PARTS,TOOLS	ACCESS TO THE ENGINE	ACCESS TO THE ENGINE
5. LABOR RATE (car)	$40/hr	$25/hr	$35/hr	$45/hr	$45/hr	$15/smog	$45/hr	$42/hr	$40/hr
6. LABOR RATE (truck)	$45/hr	$25/hr	$35/hr	$45/hr	$45/hr	$25/smog	$50/hr	$42/hr	$45/hr
7. CARB/IGNITION ADJUST	$40	$25	$10	$27.5	$12.5/32.5	$32.5	$25	$25	$20
8. FRACTION (<$50 REPAIR	NA	MOST	MOST	MOST	.95	.22	NA	.2 - .3	MOST
9. SMOG CHECKED/DAY	12 - 24	16 - 20	20 - 30	NA	40 MAX	5	3 - 4	3 - 4	16
10. SUGESTIONS	NA						TRUCKS MORE EXPENSIVE AND DIFFICULT		

RADIAN CORPORATION

SURVEY SUMMARY OF SMOG
CHECK STATIONS

QUESTION	SAC 10	SAC 11	SAC 12	SAC 13 *	SAC 14	SAC 15 *	SAC 16	SAC 17 *	SAC 18
1. REPAIR H-D TRUCKS	YES	NO	YES	YES	YES	NO	YES	NO	YES
2. INTERESTED	YES	NO	NO	YES	YES	YES	YES	YES	YES
3. ADEQUATE SPACE MAX. LENGTH	YES OUTDOORS	NO	NO	YES 30 ft	YES UNLIMITED	YES 7,100 sq ft	YES 40 ft	YES 10 ft	YES 35 - 40 ft
4. PHYSICAL CONSTRAINTS	NONE	SIZE	HEIGHT	HEIGHT 12 ft	HOSE LENGTH (TAS)	NA	NONE	VISUAL INSPECTIONS	NONE
5. LABOR RATE (car)	$30/hr	$34/hr	$37/hr	$20/smog	$40/hr	$25/smog	$42.5/hr	$15/smog	$35/hr
6. LABOR RATE (truck)	$30/hr	$34/hr	$37/hr	$20/smog	$40/hr	$25/smog	$52/hr	$15/smog	$35/hr
7. CARB/IGNITION ADJUST	$50	$15 +	NO IDEA	$30	$20	NO REPAIRS	MAKE $70 CC		$19 - 25
8. FRACTION <$50 REPAIR	.5	NA	NA	NA	SAME (car)	5 MIN/AUTO	SAME % CAR		.80
9. SMOG CHECKED/DAY	6	NA	NA	10	6		10	20 - 30	8 - 10
10. SUGESTIONS				MORE ALLOWANCES * 8 locations in Sacramento		* LICENSED TO SMOG ONLY		* LICENSED TO SMOG ONLY; 8 SAC LOCATIONS	

RADIAN CORPORATION

SURVEY SUMMARY OF SMOG
CHECK STATIONS

QUESTION	SAC 19	SAC 20	SF 1	SF 2	SF 3	SF 4	SF 5	SF 6 *	SF 7
1. REPAIR H-D TRUCKS	NO	NO	NO	NO	NO	NO	NO	YES	NO
2. INTERESTED	NO	NO	YES	NO	YES	NO	NO	YES	NO
3. ADEQUATE SPACE	NO	NO	YES	NO	YES	NO	NO	YES	NO
MAX. LENGTH			20 - 30 ft		100 ft			25 ft	6 ft
4. PHYSICAL CONSTRAINTS			TAKE TOO MUCH SPACE	NO SPACE	HOSE LENGTH INDOOR REQ.	SMALL SHOP	9.5 ft CLEARANCE	11 ft CLEARANCE	NO SPACE
5. LABOR RATE (car)	$30/hr	$42/hr	$40/hr ($10/smog)	$62/hr	$55/hr	$50/hr		$50/hr ($15/smog)	$50/hr
6. LABOR RATE (truck)		$52/hr	$40/hr		$55/hr			$50/hr	$110/hr
7. CARB/IGNITION ADJUST			$15 (car)					$32.5 (car)	$1000
8. FRACTION <$50 REPAIR					.50			.50 - .75	
9. SMOG CHECKED/DAY	1 - 2	10	5 - 10		10			10	
10. SUGESTIONS								* SAME PRICE DIFFERENT SPACE AT 6 SF LOCATIONS	

RADIAN CORPORATION

SURVEY SUMMARY OF SMOG
CHECK STATIONS

QUESTION	SF 8	SF 9	SF 10	SF 11	SF 12	SF 13	SF 14	SF 15	SF 16
1. REPAIR H-D TRUCKS	NO	NO	NO	YES	NO	NO	NO	NO	NO
2. INTERESTED	NO	NO	NO	YES	YES	NO	NO	NO	NO
3. ADEQUATE SPACE MAX. LENGTH	NO	NO	YES 25 ft	YES 18 ft	YES UNLIMITED	NO	NO	NO	NO
4. PHYSICAL CONSTRAINTS	NO SPACE	7 ft CLEARANCE		WIDTH		NO SPACE		SMALL LOT	
5. LABOR RATE (car)	$40/hr	$54/hr	$40/hr	$54/hr	$45/hr	$50/hr	$40/hr ($20/smog)	$52/hr	$45/hr
6. LABOR RATE (truck)				$64/hr	$45/hr		$40/hr	$52/hr	
7. CARB/IGNITION ADJUST				$50	$10 - 20				
8. FRACTION <$50 REPAIR					SAME (car)				
9. SMOG CHECKED/DAY				5	50 max				
10. SUGESTIONS									

RADIAN
CORPORATION

SURVEY SUMMARY OF SMOG
CHECK STATIONS

QUESTION	SF 17	LA 1	LA 2	LA 3 #	LA 4	LA 5 #	LA 6 #	LA 7	LA 8
1. REPAIR H-D TRUCKS	NO	YES	NO	NO	NO	NO	YES	NO	NO
2. INTERESTED	NO	YES	YES	YES	NO	NO	YES	NO	NO
3. ADEQUATE SPACE MAX. LENGTH	NO 12 ft	NO	NO 10 ft	YES 25 - 30 ft	NO	NO	YES 30 ft	YES 20 ft	NO
4. PHYSICAL CONSTRAINTS			SPACE	NONE	CORNER LOT NO SPACE		HEIGHT 12 ft BAR approved outdoors		HEIGHT
5. LABOR RATE (car)	$40/hr	$25/smog	$35/hr	$35/hr	$20/hr	$25/hr	$20/smog	$30/hr	$32/hr ($20/smog)
6. LABOR RATE (truck)	$40/hr	$25/smog	$35/hr	$35/hr			$20/smog	$35/hr	
7. CARB/IGNITION ADJUST		$15 - 20	$30	$30 (inc 10)			$30		
8. FRACTION <$50 REPAIR			.80						
9. SMOG CHECKED/DAY		1 - 2	5 - 6	5			10		
10. SUGESTIONS			USE THE SAME CERTIFICATE & TAS	RESEARCH AVAILIBILITY #42 licensed SMOG check in LA area		# 7 LA area locations	APPLICATIONS TABLE; REFERENCE MATERIAL # 75 LA area locations		

RADIAN CORPORATION

SURVEY SUMMARY OF SMOG
CHECK STATIONS

QUESTION	LA 9	LA 10	LA 11 #	LA 12	LA 13	LA 14	LA 15	LA 16	FRES 1
1. REPAIR H-D TRUCKS	NO	NO	YES	NO	NO	NO	YES	YES	YES
2. INTERESTED	YES	YES	YES	NO	NO	NO	YES	YES	YES
3. ADEQUATE SPACE MAX. LENGTH	YES 25 ft	YES BUS	YES 50 ft	NO	NO	NO	YES UNLIMITED	YES 35 - 40 ft	YES 20 ft
4. PHYSICAL CONSTRAINTS	NONE	if they don't run	NONE		NO SPACE		NONE; own a 6,000 sq ft vacant lot	NONE	NONE
5. LABOR RATE (car)	$30/hr	$30/hr ($19/smog)	$33/hr ($19/smog)	$30/hr	$32/hr ($20/smog)	$32.5/hr	$35/hr	$35/hr	$45/hr ($22/smog)
6. LABOR RATE (truck)	$40/hr	$60/hr	$38/hr				$35/hr	$42/hr	$45/hr
7. CARB/IGNITION ADJUST	$30	$10 - 15	$30 - 35				$30 ($50 retest)	$30 (car)	$20
8. FRACTION <$50 REPAIR	.50	.60	>.50				NONE		.60
9. SMOG CHECKED/DAY	10	6 - 8	5 - 6				3 - 5	4 - 5	6
10. SUGESTIONS							$125 - 150 REPAIR COST CEILING		wieght limit 10,000 lbs.; repair $150
			# 2 LA area locations						

SURVEY SUMMARY OF SMOG
CHECK STATIONS

QUESTION	FRES 2	FRES 3 #	FRES 4	FRES 5	FRES 6	FRES 7	FRES 8	FRES 9	FRES 10
1. REPAIR H-D TRUCKS	NO	YES	YES	NO	YES	YES	NO	NO	YES
2. INTERESTED	YES	YES	YES	NO	NO	YES	NO	YES	YES
3. ADEQUATE SPACE	NO	YES	YES	YES	NO	YES	YES	YES	YES
MAX. LENGTH	20 ft	30 ft	20 ft	30 ft		15 ft	30 ft	27 ft	30 ft
4. PHYSICAL CONSTRAINTS	HEIGHT 9 ft	HEIGHT 12 ft	NONE		NO SPACE; BUSY ENOUGH WITH CARS	SIZE		NONE	NONE
5. LABOR RATE (car)	$30/hr	$20/smog	$30/hr	$30/hr	$35/hr	$30/hr	$45/hr	$40/hr ($20/smog)	$30.5/hr
6. LABOR RATE (truck)	$30/hr	$20/smog	$30/hr			$30/hr	$45/hr	$40/hr	$30.5/hr
7. CARB/IGNITION ADJUST	$15	$30	$10					$13.5	$12.5/7.5
8. FRACTION ($50 REPAIR	SAME (car)		SAME (car)					.80	
9. SMOG CHECKED/DAY	8 max	10	2			2 - 3		2 - 3	10
10. SUGESTIONS	DON'T INCLUDE	# 5 Fresno locations	repair $100					change the TAS to test cars & trucks	

RADIAN CORPORATION

APPENDIX C

TABLE C-1. 1988 REDUCED EFFECTIVENESS I/M FAILURE RATES

Model Year	LIGHT HEAVY-DUTY GASOLINE TRUCKS (%)	MEDIUM HEAVY-DUTY GASOLINE TRUCKS (%)
1967	25	29
1968	25	29
1969	25	29
1970	25	29
1971	25	29
1972	25	29
1973	21	25
1974	21	25
1975	21	25
1976	21	25
1977	21	25
1978	18	21
1979	18	21
1980	18	21
1981	18	21
1982	13	16
1983	11	15
1984	10	13
1985	9	12
1986	7	11
1987	6	9
1988	5	9

TABLE C-2. 1988 REDUCED EFFECTIVENESS EMISSION REDUCTION DUE TO REPAIR LIGHT HEAVY-DUTY GASOLINE TRUCKS

Model Year	HC	(%) CO	NOx
1967	24	14	0
1968	24	14	0
1969	24	14	0
1970	24	14	0
1971	24	14	0
1972	24	14	0
1973	24	14	0
1974	24	14	0
1975	26	11	3.5
1976	26	11	3.5
1977	26	11	3.5
1978	26	11	3.5
1979	26	11	3.5
1980	26	11	3.5
1981	26	11	3.5
1982	26	11	3.5
1983	26	11	3.5
1984	26	11	3.5
1985	26	11	3.5
1986	26	11	3.5
1987	16	14	7
1988	16	14	7

TABLE C-3. 1988 REDUCED EFFECTIVENESS
EMISSION REDUCTION DUE TO REPAIR
MEDIUM HEAVY-DUTY GASOLINE TRUCKS

Model Year	HC	(%) CO	NOx
1967	24	26	0
1968	24	26	0
1969	24	26	0
1970	24	26	0
1971	24	26	0
1972	24	26	0
1973	24	26	0
1974	24	26	0
1975	26	14	3.5
1976	26	14	3.5
1977	26	14	3.5
1978	26	14	3.5
1979	26	14	3.5
1980	26	14	3.5
1981	26	14	3.5
1982	26	14	3.5
1983	26	14	3.5
1984	26	14	3.5
1985	26	14	3.5
1986	26	14	3.5
1987	26	14	3.5
1988	26	14	3.5

TABLE C-4. 1995 REDUCED EFFECTIVENESS I/M FAILURE RATES

Model Year	LIGHT HEAVY-DUTY GASOLINE TRUCKS (%)	MEDIUM HEAVY-DUTY GASOLINE TRUCKS (%)
1974	22	27
1975	22	27
1976	22	27
1977	22	27
1978	22	27
1979	22	27
1980	19	22
1981	19	22
1982	19	22
1983	19	22
1984	19	22
1985	16	19
1986	16	19
1987	16	19
1988	16	19
1989	11	15
1990	10	13
1991	9	12
1992	8	10
1993	6	9
1994	5	8
1995	4	7

TABLE C-5. 1995 REDUCED EFFECTIVENESS I/M EMISSION REDUCTION DUE TO REPAIR LIGHT HEAVY-DUTY GASOLINE TRUCKS

Model Year	HC	(%) CO	NOx
1974	24	14	0
1975	26	11	3.5
1976	26	11	3.5
1977	26	11	3.5
1978	26	11	3.5
1979	26	11	3.5
1980	26	11	3.5
1981	26	11	3.5
1982	26	11	3.5
1983	26	11	3.5
1984	26	11	3.5
1985	26	11	3.5
1986	26	11	3.5
1987	16	14	7
1988	16	14	7
1989	16	14	7
1990	16	14	7
1991	16	14	7
1992	16	14	7
1993	16	14	7
1994	16	14	7
1995	16	14	7

TABLE C-6. 1995 REDUCED EFFECTIVENESS I/M
EMISSION REDUCTION DUE TO REPAIR
MEDIUM HEAVY-DUTY GASOLINE TRUCKS

Model Year	HC	(%) CO	NO_x
1974	24	26	0
1975	26	14	3.5
1976	26	14	3.5
1977	26	14	3.5
1978	26	14	3.5
1979	26	14	3.5
1980	26	14	3.5
1981	26	14	3.5
1982	26	14	3.5
1983	26	14	3.5
1984	26	14	3.5
1985	26	14	3.5
1986	26	14	3.5
1987	26	14	3.5
1988	26	14	3.5
1989	26	14	3.5
1990	26	14	3.5
1991	26	14	3.5
1992	26	14	3.5
1993	26	14	3.5
1994	26	14	3.5
1995	26	14	3.5